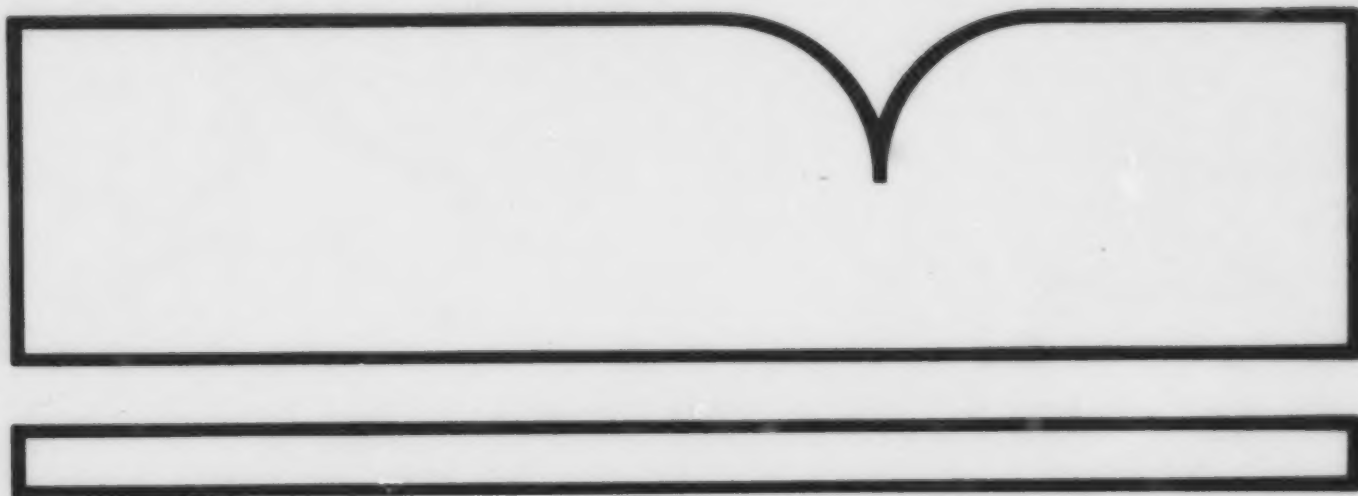


PB87-132841

Investigation of Source Emission PM-10
Particulate Matter Field Studies of
Candidate Methods

Southern Research Inst., Birmingham, AL

Dec 86



U.S. Department of Commerce
National Technical Information Service

NTIS

PB87-132841

INVESTIGATION OF SOURCE EMISSION PM-10 PARTICULATE
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Dec 86

EPA/600/4-86/042
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INVESTIGATION OF SOURCE EMISSION PM_{10} PARTICULATE MATTER
FIELD STUDIES OF CANDIDATE METHODS

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Contract 68-02-3696
Work Assignment 003 and 010

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TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA/600/4-86/042	2.	3. RECIPIENT'S ACCESSION NO. PB87 132841AS
4. TITLE AND SUBTITLE INVESTIGATION OF SOURCE EMISSION PM-10 PARTICULATE MATTER FIELD STUDIES OF CANDIDATE METHODS	5. REPORT DATE December 1986	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) William E. Farthing, Ashley D. Williamson, Sherry S. Dawes, Randal S. Martin, James W. Ragland	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southern Research Institute 2009 Ninth Avenue South Birmingham, AL 35255-5305	10. PROGRAM ELEMENT NO.	
	11. CONTRACT/GRANT NO. 68-02-3696; Tasks 003, 010	
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Research and Development Environmental Monitoring Systems Laboratory-RTP Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final	
	14. SPONSORING AGENCY CODE EPA-600/08	
15. SUPPLEMENTARY NOTES		
16. ABSTRACT This report describes the field evaluation of two candidate methods for source PM-10 measurement. The two techniques are a new sampling train design using emission gas recycle (EGR), and a Simulated Method 5 (SIM-5) approach using existing hardware with a specific traversing protocol. Four field tests were performed. At each test site, the EGR and SIM-5 measurements were compared with reference measurements of PM-10 and/or total particulate mass measurements. At two sites, the EGR and SIM-5 measurements were run simultaneously and compared to each other. The average concentrations measured using different techniques during each test agreed within the combined 95 percent confidence intervals. In paired-run analysis of the simultaneous measurements, the confidence intervals are smaller and some observed differences are found to be statistically significant. Such differences, even when significant at the 95 percent confidence level, are typically on the order of 10 percent varying in direction from site to site. The PM-10 measurements in these tests using each technique compared well with the other and with those using other reference techniques. The test results are presented and the conclusions derived from these results discussed. Also, recommendations are made for procedural and hardware refinements of each method, and for further tests at many stationary sources.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Emission Measurement of PM-10 PM-10 Stationary Source Measurement Emission Measurement Methods, PM-10 Stationary Sources Source Emission Measurement, PM-10		
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 144
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

DISCLAIMER

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FOREWORD

Measurement and monitoring research efforts are designed to anticipate environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations, and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Environmental Monitoring Systems Laboratory, Research Triangle Park, North Carolina, has responsibility for: assessment of environmental monitoring technology and systems for air, implementation of agency-wide quality assurance programs for air pollution measurement systems, and supplying technical support to other groups in the Agency including the Office of Air and Radiation, the Office of Toxic Substances, and the Office of Solid Waste.

Regulations for ambient levels of PM-10 particulate matter have been proposed by the Agency. Probable causes of the ambient PM-10 levels include agricultural activities, use of both paved and dirt roads, various natural causes including winds, construction and destruction, other activities which disturb the earth's surface, mobile sources and stationary sources. Acceptable measurement methodology is critical for proper assessment of the emissions by stationary sources of PM-10 particulate matter. This study was undertaken to perform research and development work on methods for the quantification of PM-10 particulate matter emissions from stationary sources.

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ABSTRACT

This report outlines the results of four field tests of two candidate methods for source PM_{10} measurement. The first method involves a new sampling train design which incorporates emission gas recycle (EGR) to avoid the anisokinetic sampling bias inherent in size specific emissions measurement. The second technique, the simulated Method 5 (SIM-5) approach, uses existing sampling hardware with an altered traversing protocol to minimize this bias.

The first and second field tests were shakedown tests for EGR and SIM-5, respectively. The third test was a direct comparison of EGR to SIM-5 and both to an independent technique, or single point impactors operated at isokinetic flowrates. The fourth test compared EGR to SIM-5 at the inlet to a control device and SIM-5 to Method 17 at the control device outlet.

The average concentrations measured using different techniques during each test agreed within the combined 95% confidence intervals. In paired-run analysis of the simultaneous measurements, the confidence intervals are smaller and some observed differences are found to be statistically significant. Such differences, even when significant at the 95% confidence level, are typically on the order of 10% and are not consistent in direction from site to site. We conclude that PM_{10} measurements using each technique can be expected to compare well with the other and with those using other reference techniques. Likewise, EGR measurements of total mass concentration may be expected to compare well with Method 17 measurements where particulate catches are sufficient to allow good recovery from the EGR sampler. Although SIM-5 was designed primarily for measurement of PM_{10} concentrations, in the present test series SIM-5 total mass measurements fell within 15% of values from the EGR and other isokinetic samplers.

The results of this test series suggest that both techniques are sufficiently advanced that they should be documented in more detail for potential use as sampling methods. Further, more extensive testing should be performed in order to define precision, reproducibility, and comparability of each technique as well as identify potential sources of interference or bias. Also, it is recommended that further development of both techniques continue to refine procedural details and investigate hardware improvements made apparent during field use of the two methods.

This report was submitted in fulfillment of Contract No. 68-02-3696 by Southern Research Institute under the sponsorship of the U.S. Environmental Protection Agency.

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SECTION I

INTRODUCTION

A size-specific PM_{10} ambient-air particulate standard has been proposed and promulgation is expected. The introduction of size into the definition of suspended particulate matter in the ambient air suggests the need for measurement of size-specific emissions from stationary sources. Technology related to such measurements has been developed in connection with evaluation of control devices on process streams. Inertial impactors and cyclones can separate or classify aerosol particles in situ but are more complex to operate than total particulate mass trains. Furthermore, operation of these devices for typical engineering evaluation purposes does not require the documented accuracy and reproducibility desired for emissions inventory development or compliance purposes.

The Quality Assurance Division of the Environmental Monitoring Systems Laboratory (EMSL/RTP) has initiated a research program to develop source measurement techniques to support the proposed PM_{10} standard. The first (development) phases of this program were conducted under contract by Southern Research Institute. This work has focused on two promising techniques for source PM_{10} measurement. The first involves a new sampling train design which incorporates emission gas recycle (EGR) to avoid isokinetic sampling bias. The second, the simulated Method 5 (SIM-5) approach, uses existing sampling hardware with an altered traversing protocol to minimize this bias.

The present work assignments represent the latest of several related research projects sponsored by the EPA. The EGR concept was articulated by D. B. Harris of IERL/RTP, who developed a prototype research train (Harris, 1981). This device was modified and upgraded at Southern Research Institute under various technical directives of EPA Contract 68-02-3118. The SIM-5 approach was conceptualized by T. E. Ward of EMSL/RTP and developed by Southern Research Institute under the same contract. Under the present work assignments, both techniques were tested in four field excursions, representing three tests for each technique.

Section II of this report gives conclusions and recommendations concerning the EGR and SIM-5 sampling techniques. The techniques are described in Section III. Then each of the next four sections, Sections IV - VII, describe field tests of the techniques. The first and second field tests were shakedown tests for EGR and SIM-5, respectively. The third test was a direct comparison of EGR to SIM-5 and both to an independent technique, single point impactors operated at isokinetic flowrates. The fourth test compared EGR to SIM-5 at the inlet to a control device and SIM-5 to Method 17 at the control device outlet. Section VIII gives conclusions and recommendations related to PM_{10} beyond direct concerns with EGR and SIM-5. Section IX summarizes the Quality Assurance Procedures involved in this work assignment. Original raw data in run sheets and computer printouts for all of the tests are included in a separate field test compendium.

SECTION II

CONCLUSIONS AND RECOMMENDATIONS

Sections IV - VII describe four field tests in which the EGR, SIM-5, or both techniques were evaluated. General conclusions from all field tests are detailed in Section VIII and summarized in this section. Both the EGR and SIM-5 techniques for PM_{10} performed well in the four field tests. In every case, the average concentrations measured using different techniques agreed within the combined 95% confidence intervals. In paired-run analysis of the simultaneous measurements, the confidence intervals are smaller and some observed differences are found to be statistically significant. Such differences, even when significant at the 95% confidence level, are typically on the order of 10% and are not consistent in direction from site to site. We conclude that PM_{10} measurements using each technique can be expected to compare well with the other and with those using other reference techniques. Likewise EGR measurements of total mass concentration may be expected to compare well with Method 17 measurements where particulate catches are sufficient to allow good recovery from the EGR sampler. Although SIM-5 was designed primarily for measurement of PM_{10} concentrations, in the present test series SIM-5 total mass measurements fell within 15% of values from the EGR and other isokinetic samplers.

We have several recommendations for further study which are also described in more detail in Section VIII. First, both techniques are sufficiently advanced that they should be documented in more detail for potential use as sampling methods. Second, they should be subjected to more extensive validation and collaborative testing than was possible during this project to define further precision, reproducibility, comparability with other measurements, and possible sources of interference or bias using each technique. It is also recommended that further development of both techniques continue to refine procedural details and investigate hardware improvements. These include development of an EGR impactor train, further characterization of impactor precutters and the existing PM_{10} Cyclone (SoRI-I), investigation of an alternate geometry Cyclone I, and investigation of the optimum use of S-type pitot tubes with instack PM_{10} samplers.

SECTION III

DESCRIPTION OF CANDIDATE PM₁₀ TECHNIQUES

The technical difficulties in size-specific (i.e., PM₁₀) particulate sampling are greater than, but similar to, those of total particulate sampling by EPA Reference Methods 5 or 17. Potential sampling biases exist because of variations in the spatial distribution of particulate concentrations across the sampling plane defined by the duct cross-section. Likewise, temporal variations in particulate concentrations due to process variations can cause inaccurate or unrepresentative emissions measurements. EPA reference methods for particulate sampling (Methods 5 and 17) deal with these problems by specifications on the sampling location to minimize stratification (Method 1) and by spatial and temporal averaging using a traversing protocol which collects a weighted average of the particulate emissions at an array of points spanning the sample plane. Method 5 specifications also require at least 3 separate measurements, allowing further temporal averaging. A second potential error in particulate measurements is duct/nozzle sampling bias. Unless the gas velocity, u , entering the sampling nozzle equals the local duct velocity, v , particulate matter will be selectively depleted or enriched in the sample gas stream due to inertial separation at the nozzle entrance. The effect of anisokinetic sampling has been characterized by Belyaev and Levin (1974) in terms of an aspiration coefficient, A , defined as measured concentration/actual concentration:

$$A = 1 + (R-1) \frac{B}{B+1} \quad (3-1)$$

where R = velocity ratio v/u

$B = (2 + 0.617/R)K$,

K = particle Stokes number with respect to the nozzle, $\tau v/d$,

τ = particle relaxation time $CD^2/18\mu$ (sec),

C = Cunningham slip factor,

D = particle aerodynamic diameter (cm),

μ = gas viscosity (poise), and

d = nozzle diameter (cm).

Note that B is proportional to particle diameter squared so anisokinetic sampling bias becomes more pronounced as particle diameter increases. For total particulate sampling, this bias may be restricted by specifying isokinetic sampling (within a 10% tolerance) at each point. This tolerance is easily attained in sampling which is not size specific by varying the sample flowrate so that nozzle velocity is within 10% of stream velocity.

These potential problems are enhanced in PM₁₀ sampling by the fact that inertial size segregation must be performed. Any inaccuracies in the inertial cutoff diameter, which is determined by sample flowrate, will lead to errors in the PM₁₀ measurement by misclassification of particulate matter in the size range near 10 μm . Misclassification of particles larger than 10 μm can also occur due to bounce or reentrainment, causing these particles to be counted in the PM₁₀ fraction. Likewise, if extensive deposition of particles smaller than

10 μm occurs upstream of the inertial sizing device, then the PM_{10} fraction will be depleted even if the nozzle deposits are reentrained as agglomerates and pass into the sizing stage. All these potential problems must be faced in a PM_{10} sampling strategy.

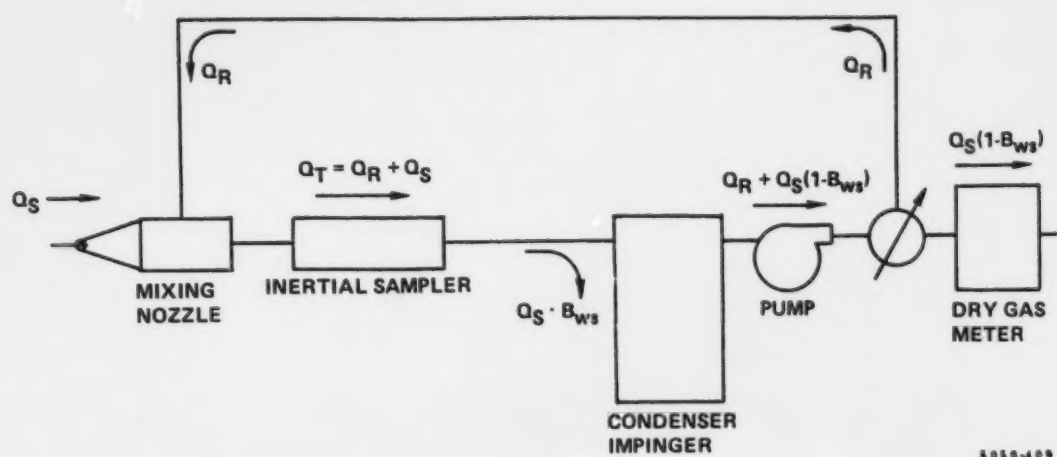
The most obvious potential inaccuracy in PM_{10} sampling is due to a "built in" anisokinetic sampling bias. Inertial sizing devices (impactors and cyclones) are available which have a sufficiently sharp collection efficiency cut at 10 μm , but only for specified flowrates which are dependent on gas temperature and composition. Without a sampling nozzle of continuously variable cross-sectional area, this fixed flowrate requirement makes isokinetic sampling in the manner of Method 5 impossible. Since anisokinetic sampling bias can be significant for particles near 10 μm , this effect cannot be ignored.

Previous work on this problem at Southern Research Institute has led to the development of two potential sampling methods - the Emission Gas Recycle (EGR) sampling train, and the Simulated Method 5 (SIM-5) traversing protocol. The EGR Train in principle eliminates the problem of anisokinetic sampling bias by simultaneously allowing isokinetic sampling at the nozzle and fixed flow operation at the inertial sizing device(s). The train design allows the isokinetic flow of gas into the sampling nozzle to be augmented by an adjustable amount of filtered, recycled stack gas upstream of the inertial sizing device. The SIM-5 protocol is an alternate candidate PM_{10} method which uses existing sampling equipment (cyclones or cascade impactors without special gas recycle adaptations). The protocol involves synthesizing a duct traverse with fixed flowrate runs, using different sampling nozzles if necessary so that the nozzle velocity at each sample point does not fall outside a specified range relative to the isokinetic velocity at that point. Both techniques are described further in the remainder of this section.

EMISSION GAS RECYCLE (EGR) TRAIN

The principle of operation of the EGR train is illustrated in Figure 3-1. Stack gas is extracted isokinetically at volumetric flowrate Q_s . If the stack moisture fraction is B_{ws} , the sample flow consists of $Q_s \cdot B_{ws}$ moisture and $Q_s(1 - B_{ws})$ dry gas flow. At the mixing point a flow, Q_r , of dry reheated recycle gas is added to the sample stream to bring the total flowrate to the predetermined constant level, Q_t . In the impingers or condenser, the moisture content $B_{ws} \cdot Q_s$ is removed. After the pump and total flow metering element, the recycle flow Q_r is diverted by means of an adjustable valve. By mass balance, in a leak-free system the remaining flow which passes the dry gas meter and orifice will simply be $Q_s(1 - B_{ws})$ exactly as would occur in an isokinetic sampling train without gas recycle.

There are several practical requirements for a functional EGR sampling system. The operator must be able to monitor and control accurately two flowrates rather than one. Setup and operation of the train must be simple, and the train must function reliably in normal field sampling environments. The recycle gas mixing must not cause significant particle deposition, must not perturb the cutpoints of the inertial sizing device, and must not introduce



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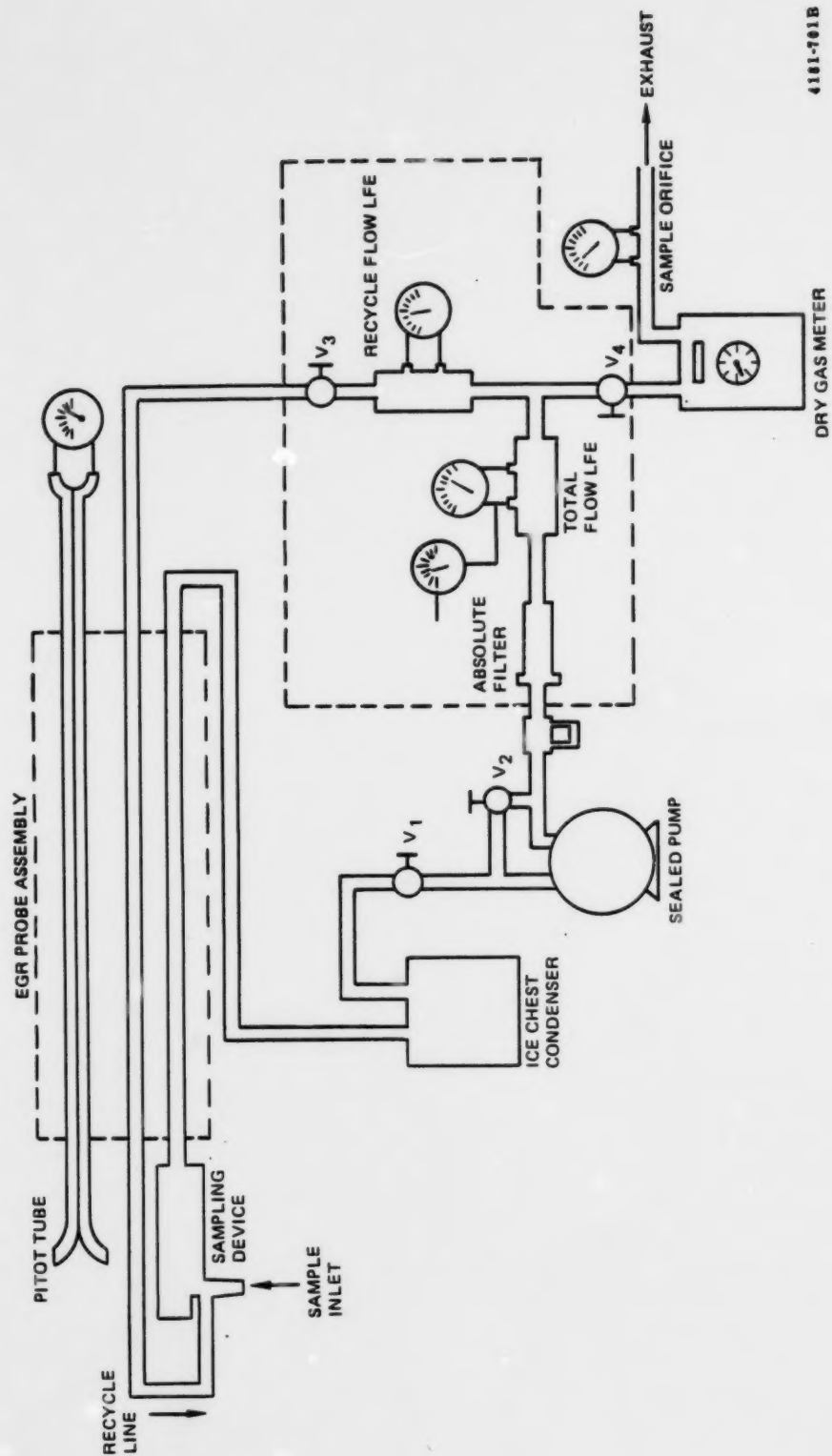
Figure 3-1. Gas flow in emission gas recycle (EGR) train.

artifact particulate matter. In order to meet these constraints, the EGR train was constructed by modifications to the control module and sampling hardware of a commercially available Method 5 sampling train. Laminar flow elements are used to monitor the recycle and total flowrates. In order to minimize particulate losses, the recycle gas is introduced coaxially in an annulus around the sample gas.

A block diagram of the prototype field EGR train is shown in Figure 3-2. Stack gas is isokinetically extracted through the sample portion of the EGR mixing nozzle, mixed with the conditioned recycle gas and then passed into Cyclone SoRI-I, the initial sizing component of the sample train. After passing the inertial sizing device and instack sample filter, the sample gas passes through the probe and condenser or impinger train and into the EGR flow control module. As in conventional Method 5 control modules, the gas flowrate entering the control module is controlled by coarse and fine control values (V_1 and V_2 , respectively) at the entrance of the sealed pump. At the exit of the pump and absolute filter, the total flow is measured using a laminar flow element (LFE- Meriam Model 50MJ10-1/2 Type 10). The gas stream is then split into the recycle and sample flow lines. The sample flow is monitored in the normal manner using a dry gas meter and a calibrated orifice. The recycle gas flowrate is measured using a second laminar flow element (Meriam Model 50MJ10-1/2 Type 11). The partitioning between sample and recycle gas is controlled by a valve (V_3) located downstream of the LFE. Valve V_4 was added to the system to extend the range of control to higher recycle percentages by adding back pressure to the sample flow line. Figures 3-3 through 3-5 show various views of the EGR pump module (modified Method 5 control unit).

The recycle gas line, along with the sample and pitot lines, passes through the heated probe in which the recirculated gas is reheated to the duct temperature. Power to the heater is regulated by a proportional temperature controller using a thermocouple reference sensor located in the gas stream downstream of the heater. Figure 3-6 shows the EGR "suitcase" control panel developed to monitor and control the various pressure differentials (from the LFE's) and temperatures of the EGR sampling system. Flexible tubing is used to connect the magnehelics of the control panel to the laminar flow elements in the pump module. The major components of the EGR sampling system, including an ice-bath condenser, are shown in Figure 3-7.

Operation of the EGR train is similar to standard Method 5 sampling. The total dry gas flow $Q_t + Q_s(1 - B_{ws})$ is monitored by using the total flow LFE and controlled using values V_1 and V_2 . The sampling flow Q_s (defined as the gas flowrate entering the nozzle) is monitored using the sample orifice and dry gas meter in the normal manner of Method 5 sampling, and controlled using the recycle value V_3 . Selection of traverse points and sample flowrate are done using standard techniques. In practice, the total flow would first be set to its operating value for the desired size cut(s), then the sample flowrate adjusted to be isokinetic at the first traverse point. Changes in the recycle flow setting alter the total flow only slightly, so that one or two quick iterations of V_2 and V_3 are needed at a new traverse point. V_4 needs only to be adjusted once before a sample run to insure that the maximum necessary recycle flow can be attained. The only aspect that may be initially confusing



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Figure 3-2. Schematic of the emission gas recycle train.

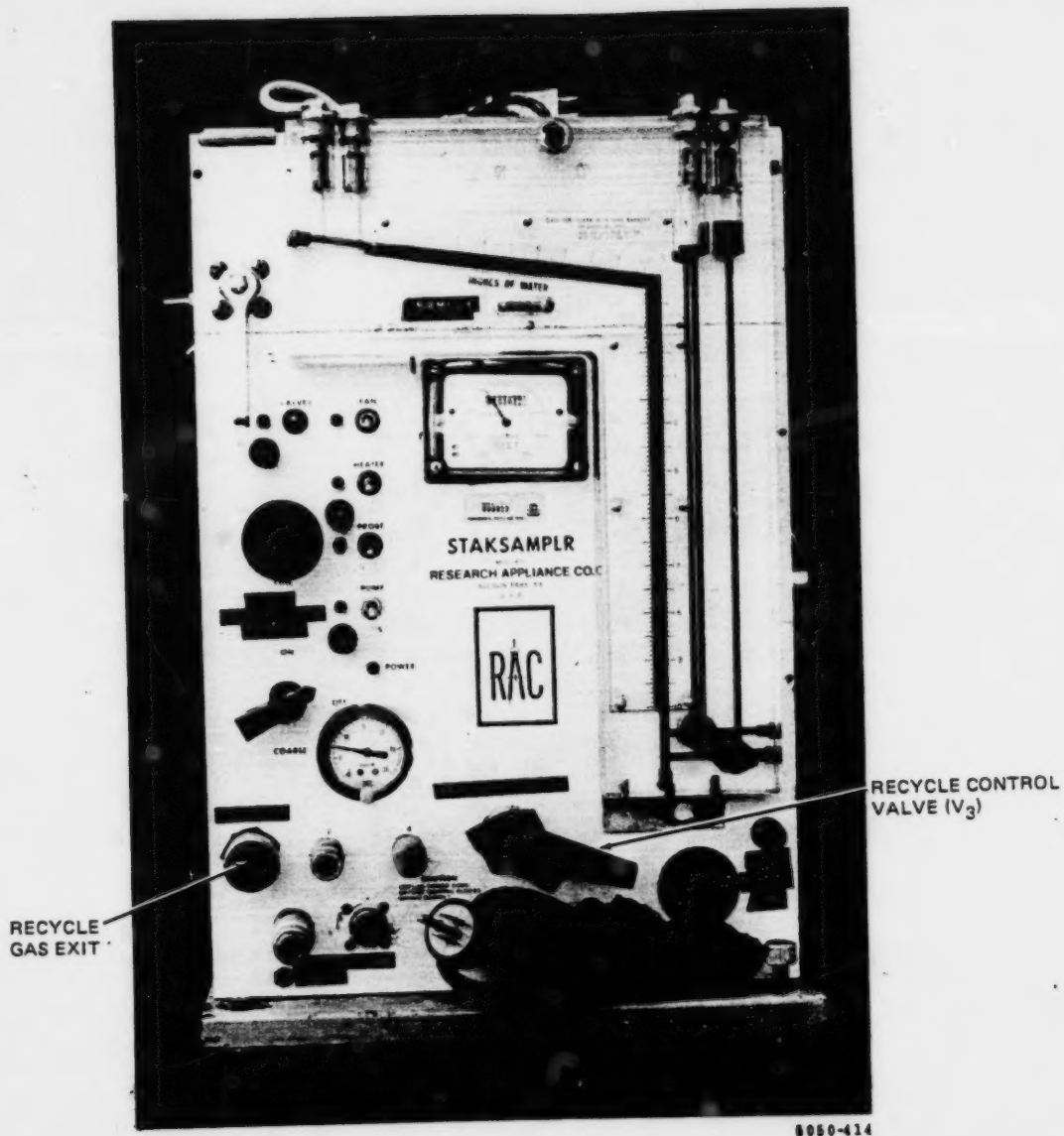


Figure 3-3. EGR Control Console (Front View).

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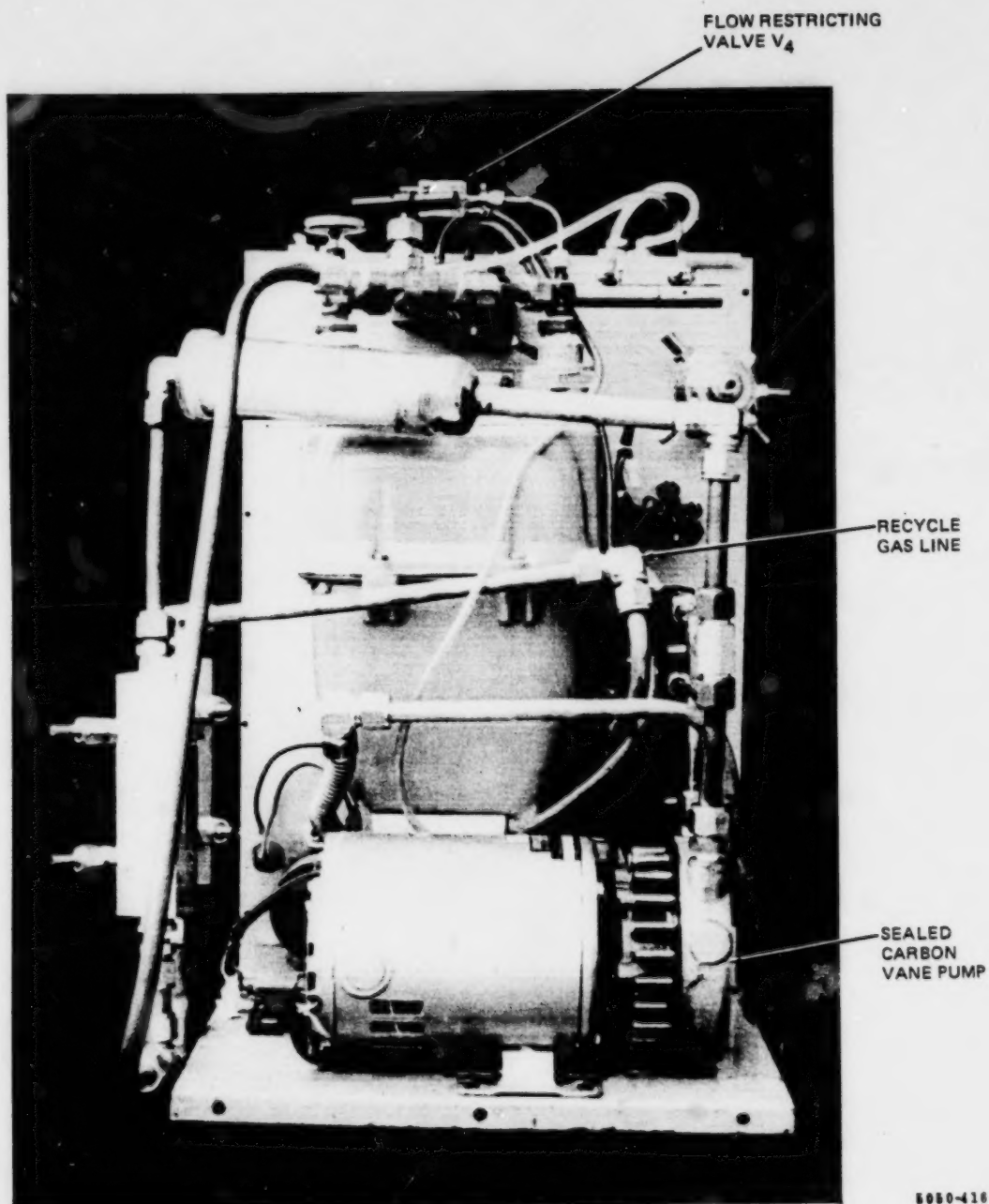
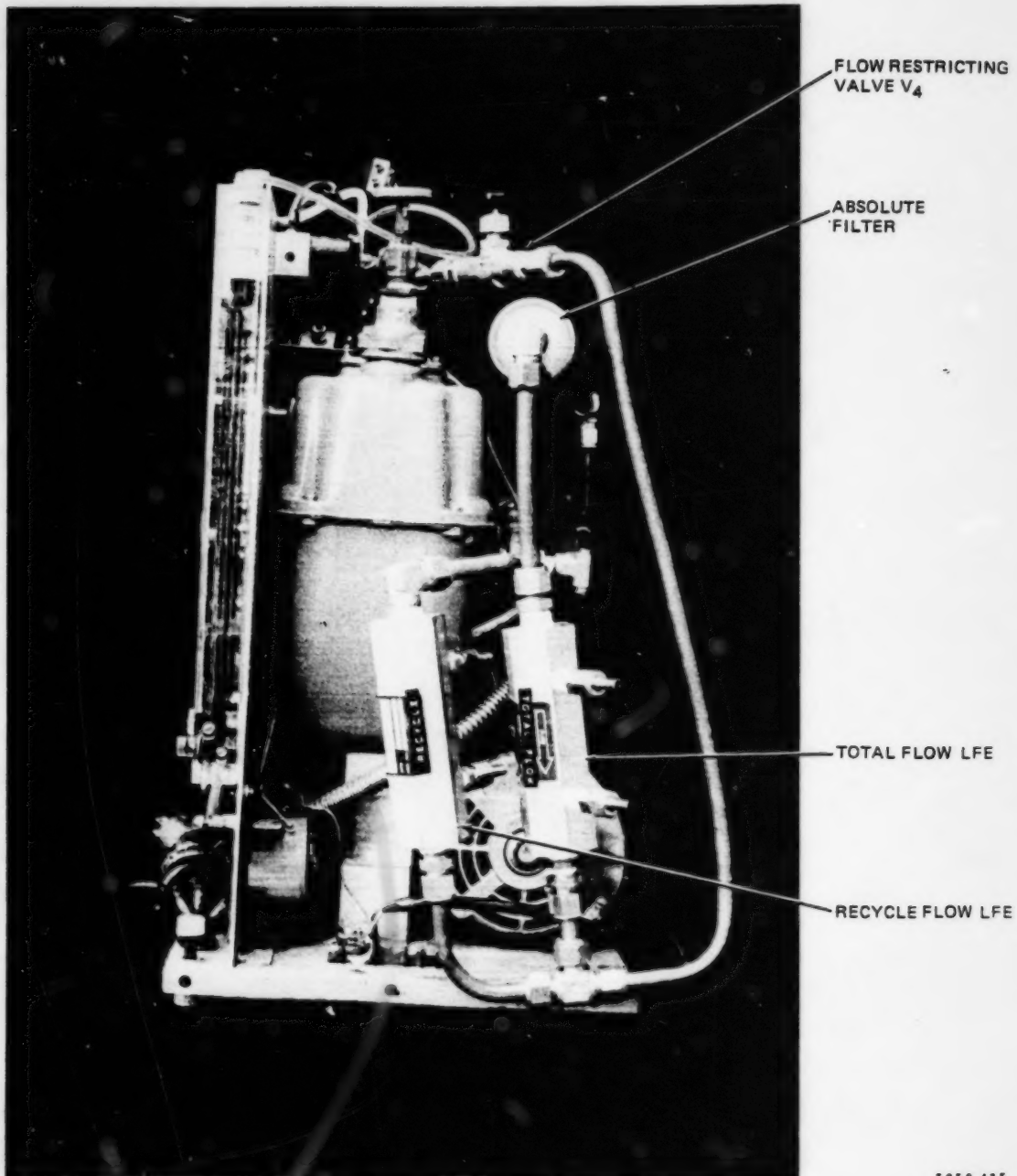


Figure 3-4. EGR Control Console (Rear View).

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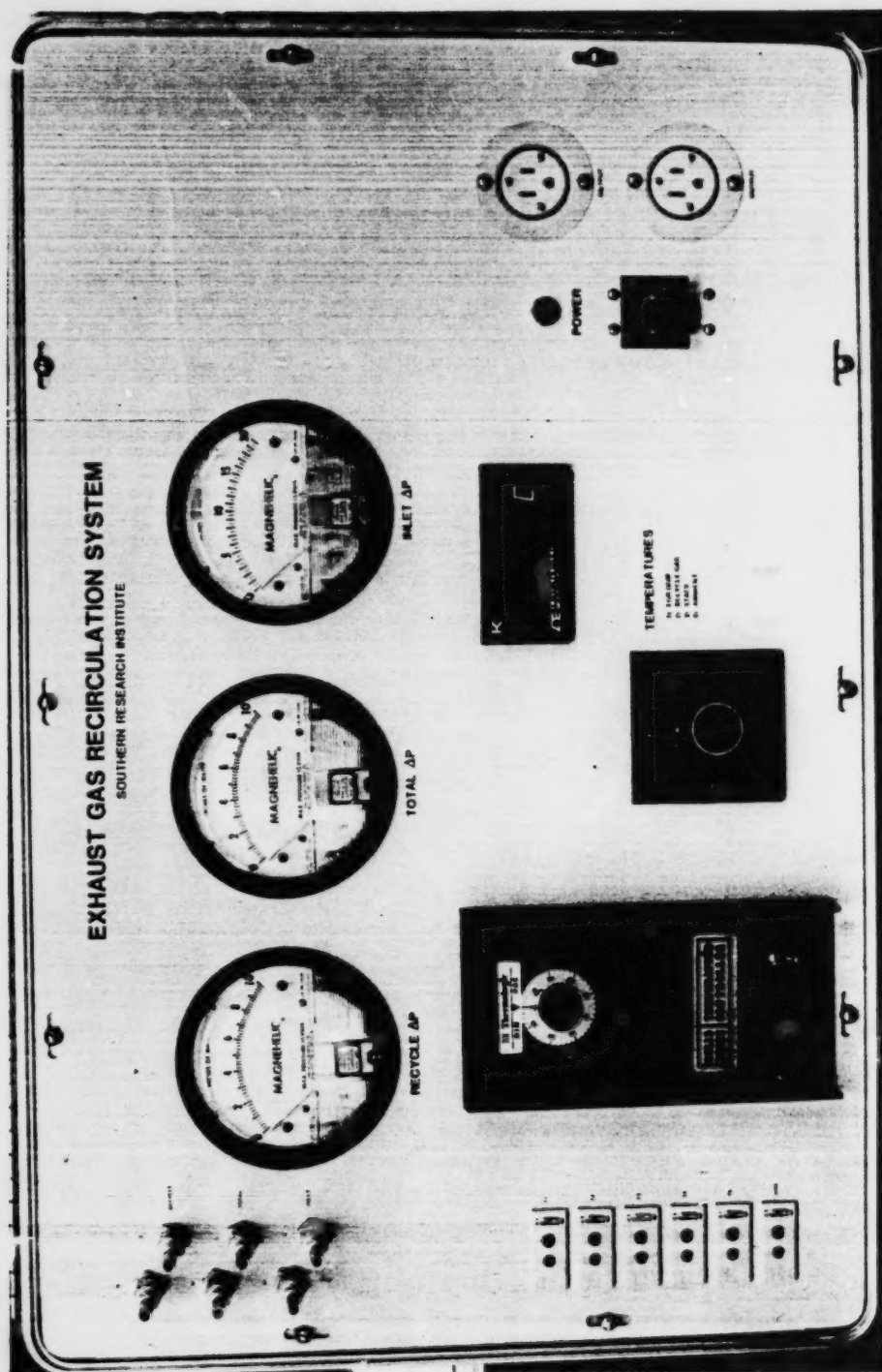




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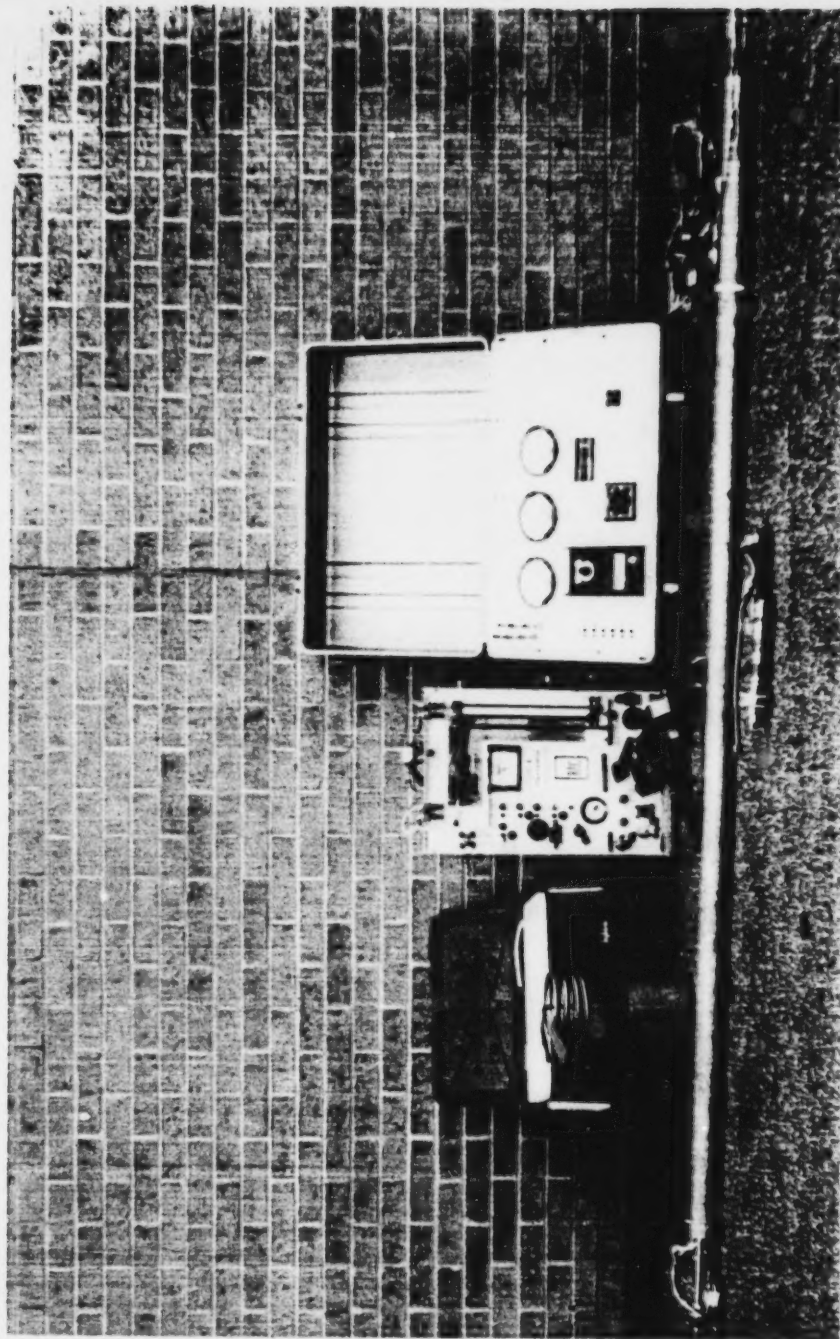
Figure 3-5. EGR Control Console (Side View).

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Figure 3-6. EGR auxiliary control module.



5060-420

Figure 3-7. EGR Sampling System.

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to a trained Method 5 operator is that the sample flowrate is adjusted using the recycle valve rather than the customary valves V_1 and V_2 .

SIMULATED METHOD 5 (SIM-5) TECHNIQUE

The EGR train offers the potential to allow routine PM_{10} sampling without greatly exceeding the accuracy, cost, and complexity expected for Method 5 sampling. At present, however, EGR sampling equipment is still in developmental stages and is not commercially available. It is not certain if or when this technique will be commercialized, and if it will be suitable for all emission gas streams of interest. The SIM-5 technique was developed to allow immediate PM_{10} sampling with commercially available equipment.

As discussed in the introductory paragraphs, potential errors in PM_{10} sampling arise from several sources. First, spatial variation of particulate concentrations across the duct cross section will cause sampling bias. The magnitude of this bias is generally reduced by increasing the number of sampling points traversed. Other sources of error, such as temporal variations in the emissions and random measurement uncertainties, likewise may be reduced by increasing the number of samples. Finally, errors due to anisokinetic sampling depend on several factors which can be only partially controlled, such as the magnitude and variation of the stream velocity over the traverse grid, the sample flowrate chosen, and the particle size distribution. These errors were analyzed in detail in the final report to the SIM-5 development task of EPA Contract 68-02-3118 (Farthing, 1983).

Several potential PM_{10} sampling protocols can be imagined which use existing inertial sizing equipment. In theory, an inertial sizing train can be run using a full Method 5 isokinetic traverse. This option is unrealistic for PM_{10} since the inertial size cuts are defined only if the gas flowrate remains constant during a sample run. A second option is to sample a representative traverse grid (chosen by Method 1 or other criteria) at a constant flowrate determined by the inertial sizing device. This option is the one usually chosen for particle size distribution measurements. Typically, when this option is chosen enough traverse points are used so that the dominant error source is expected to be anisokinetic sampling bias. At the other extreme, the operator may choose to minimize isokinetic sampling bias by operating the PM_{10} sampler at near-isokinetic conditions at a single point. In this case, errors due to spatial variation are expected to dominate unless a traverse is synthesized by multiple single-point samples at different duct positions. The sampling option expected to have greatest accuracy is a synthesis of several single-point, near-isokinetic runs into a traverse. This option unfortunately is the most expensive in terms of on-site sampling time. Other sampling protocols may be suggested. For example, one approach which has been used involves replicate single-point cascade impactor sampling to obtain a measure of the PM_{10} fraction of the particulate emissions. This fraction is applied to the total mass concentration or emission rate (as determined by Method 5) to obtain a value for the PM_{10} concentration.

All of the protocols generally outlined above involve compromises between cost and total measurement uncertainty. For different choices of sampling

strategy, the measurement uncertainty may be dominated by spatial or temporal variation of particulate emissions, by anisokinetic sampling bias, or by inherent errors of measurement. Typically, sampling strategies for specific sites are developed without a clear quantitative picture of the magnitude and dominant source of the measurement inaccuracy to be expected.

In developing a candidate SIM-5 strategy (Farthing, 1983) an approach was selected which allows expected measurement errors to be contained within predetermined limits. The objective of the protocol is to minimize total costs while reducing anisokinetic sampling errors to the approximate range expected from spatial and temporal variation of emissions. Anisokinetic sampling bias is kept in this range by synthesizing a full duct traverse from partial traverses at constant sample flowrate. Points for each partial traverse are selected which have duct velocities in the range to keep anisokinetic sampling errors for 10 μm particles below $\pm 20\%$ at each point. Actual errors at sites in this test series are estimated to be less than about $\pm 12\%$ because PM_{10} includes all particles with aerodynamic diameters less than 10 μm , aerosols encountered in process streams have substantial mass fractions at sizes well less than 10 μm , and error due to anisokinetic sampling decreases with the inverse of size to the second power (Farthing, et al., 1985). Since for most sources combined spatial and temporal variation can be kept within $\pm 10\%$ for traverses of 8 to 12 points (Shigehara, 1982), this number of points was chosen. The sampling protocol used in these field studies is outlined in Table 3-1. More details are given in later sections in association with its use in the field tests of this project.

INERTIAL SIZING DEVICES

In the course of this field measurement program, size specific particulate measurements were made with two inertial sizing devices. Direct PM_{10} size fractionation was performed using the first cyclone of the SoRI/EPA Five Stage Series Cyclone sampling train (Smith, et al. 1979). This cyclone was used for all EGR testing and much of the SIM-5 testing. The remainder of the SIM-5 testing and other reference size distribution measurements were performed using University of Washington Mark V Cascade Impactors. Technical details concerning the use of the cyclones are given in the following sections.

PM_{10} Cyclone SoRI-I

While the EGR approach should be adaptable to most inertial sizing devices, it has been implemented only using SoRI Cyclone-I as a PM_{10} collector. The EGR/Cyclone I train may be used as a single stage PM_{10} sampler, or other cyclones or impactors may be added downstream of Cyclone I to provide further size fractionation. In this test series, two cyclone configurations were used. A dual cyclone train consisting of Cyclone I and Cyclone IV of the SoRI/EPA Five Stage Series Cyclone train was used in EGR Test 1 and in EGR/SIM-5 Test 2. This train allowed recovery of a fine particle fraction (smaller than approximately 2.5 microns aerodynamic diameter) as well as a PM_{10} concentration. The full Five Stage Cyclone Train was used at EGR/SIM-5 Test 3 to provide more detailed size distributions.

Table 3-1

RECOMMENDED SIM5 PROTOCOL FOR PM_{10}

- (a) Perform a velocity traverse of 8 points if sampling in a stack, 8 diameters above the nearest disturbance, or 12 points at other locations at least 2 duct diameters from the nearest disturbance. The measured values are designated v_n . Calculate the average velocity, v_o .
- (b) Perform gas analysis.
- (c) Determine the actual flowrate, Q_A (at stack conditions) for a $10 \mu m$ aerodynamic cutpoint of PM_{10} sampler. This will be a function of stack gas viscosity.
- (d) Calculate the product $\mu/\sqrt{Q_A}$ with Q_A in alpm and μ in micropoise for the sampling runs to be performed. Then identify the upper and lower curves in Figure 3-8 with $\mu/\sqrt{Q_A}$ nearest but less than the value calculated for the runs to be performed. These two curves are designated $R_{max}(v)$ and $R_{min}(v_n)$.
- (e) Calculate nozzle velocity ($u_m \equiv 4Q/\pi d_m^2$) for each available nozzle and $R_{mn} = (u_m/v_n)$ for each sampling point with each nozzle. Then choose the desired combinations (m,n) of nozzles and sampling points for which R_{mn} lies between R_{max} and R_{min} from Figure 3-8. If more than one nozzle satisfies this criterion for a sampling point n, then choose the combinations (m,n) which minimize the number of different nozzles (or separate sampling runs) required.
- (f) Perform a sampling traverse composed of one sampling run with each nozzle. Operate the probe during each run according to recommended operating procedure for the inertial sampler used. During each run position the probe nozzle at the points appropriate for the current nozzle, defined by the combinations (m,n) obtained in the preceding step (e). The time of sampling at each point should be proportional to the velocity at that point.
- (g) Obtain a PM_{10} concentration for each run, W_m , then calculate total PM_{10} emission rate, E, from

$$E = \frac{1}{M} \sum_{m=1}^M \frac{1}{N_m} \sum_{j=n(m)}^{8 \text{ or } 12} v_{m,j} W_m$$

where M = the number of nozzles or runs

N_m = the number of points sampled with each nozzle, m, and
 $n(m)$ = the point index numbers for each nozzle.

- (h) Repeat (a)-(g) three times and calculate an average emission rate.

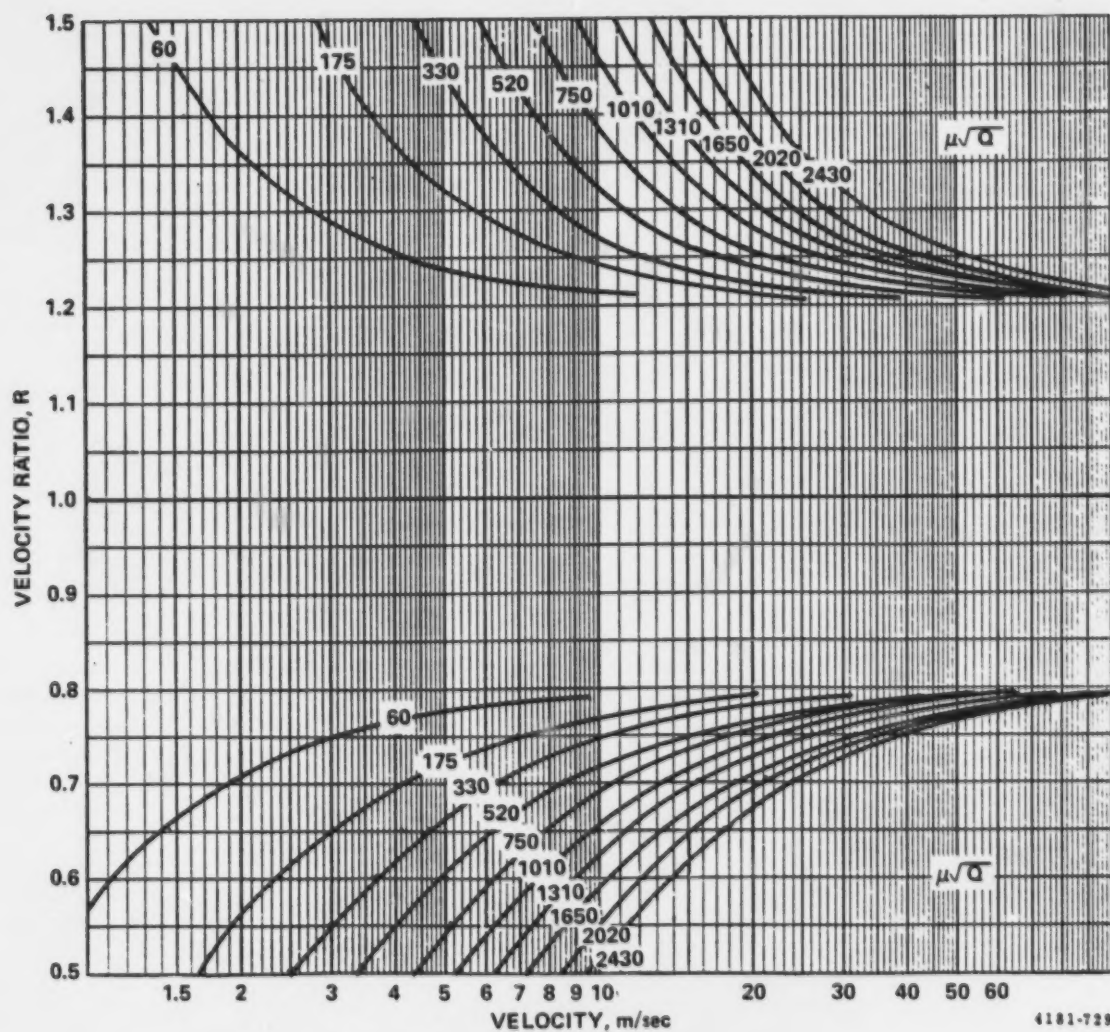


Figure 3-8. Velocity ratio R , duct velocity/nozzle velocity, versus duct velocity giving aspiration coefficient of 1.2 (upper curves) and 0.8 (lower curves) for particles with aerodynamic diameter of $10\ \mu\text{m}$ and gas viscosities ranging from 160 to 280×10^{-6} poise. Sampling error of $10\ \mu\text{m}$ particles is less than $\pm 20\%$ for R -values between an upper and a lower curve.

PM₁₀ Flowrate--

The flowrate through Cyclone I was set to produce a predicted 10 μ m aerodynamic D₅₀ for the first cyclone. This flowrate was determined from calibration data reported previously (Smith, et al. 1979) plus calibration results at additional flowrates and temperatures, obtained in the laboratory during the course of this project and EPA project 68-02-3118. Figure 3-9 shows the calibration data available previously for Cyclone I with the additional data obtained recently. The recent calibrations used monodisperse aerosols with aerodynamic diameter near 10 μ m. These calibrations were performed after it became apparent that deriving PM₁₀ flowrates from the original data required extrapolation beyond the range of validity of this data. The additional data provide a good measure of the PM₁₀ flowrate at two temperatures, and extend the Cyclone I database to allow a more accurate fit at other temperatures.

A satisfactory theory for cyclone behavior does not exist so estimation of the appropriate PM₁₀ flowrate with limited calibration data was performed using a semi-empirical approach. The dependences of D₅₀ upon temperature (actually viscosity, μ) and flowrate, Q, are assumed independent in log-space. The data at low temperature suggest that log D₅₀ is essentially a linear function of log Q. The data at constant Q suggest, when graphed, that log D₅₀ is essentially a linear function of log μ . Thus a function of the form

$$D_{50} = A \mu^a Q^b \quad (3-2)$$

was fit to the data. The results are $a = 1.39$, $b = -0.624$, and $A = 8.42 \times 10^5$ for aerodynamic D₅₀ in microns, μ in poise and Q in acfm. For a D₅₀ of 10 μ m, Q_{PM₁₀} is then given by

$$Q_{PM_{10}} = (7.82 \times 10^7) \mu^{2.23} \quad (3-3)$$

in the same units.

The new data shown in Figure 3-9 were obtained during the course of the sampling program, and were not available before the start of the field testing. Thus, fits to the previous data or preliminary calculations were used to calculate the PM₁₀ flowrate for setup of cyclones in EGR Test 1 and combined EGR/SIM-5 Test 2. Equation (3-3) was used for setup calculations in the final test. In data reduction for all three tests, equation (3-2) was used to calculate the D₅₀ for Cyclone I.

Cyclone IV Versions--

SoRI Cyclone IV was used as part of the EGR and comparison trains in all three test series. In all tests, the test plan required simultaneous operation of the EGR cyclone train and the comparison train (STD for Test 1 and SIM-5 for the last two tests). The test objectives included primarily comparison of total mass and PM₁₀ concentration measurements of the two trains and secondarily comparison of the fine particle fraction or fractions. This secondary purpose was frustrated by an equipment anomaly that was not discovered until after the final test of the series. Two different versions of Cyclone IV were used in the two cyclone trains. The comparison train contained the original design of Smith et al. (1979). The cyclone train used in the EGR setup (as well as all commercially available versions of the series cyclones)

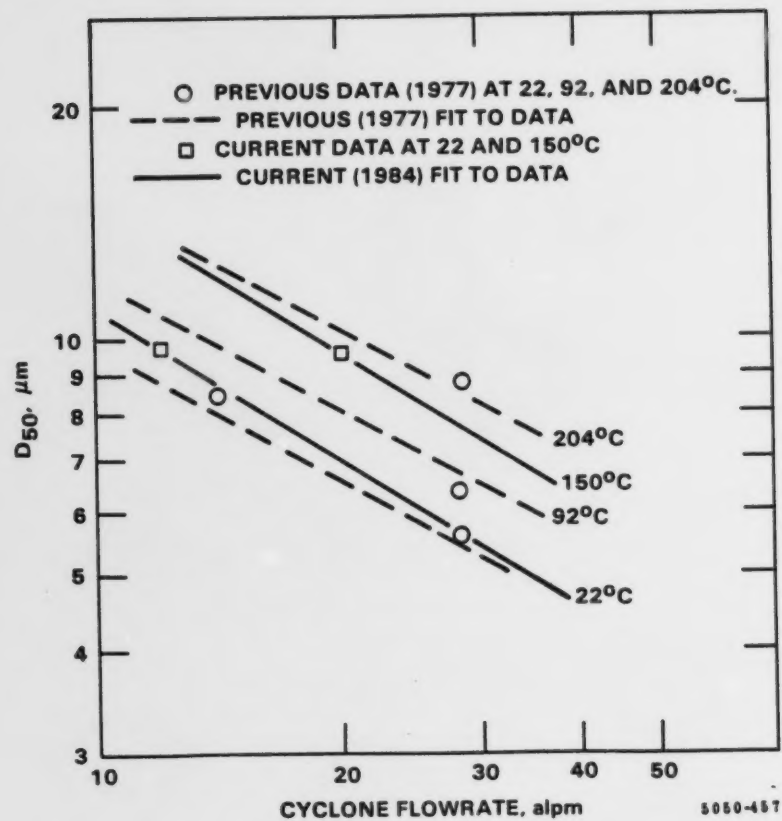


Figure 3-9. Cyclone I D_{50} versus flowrate at various temperatures.

contain a shorter, modified version of Cyclone IV developed in 1978. The cutpoint of this cyclone has not been characterized, but is clearly different from the original. This fact is seen in the size distributions measured in this project, which indicate that the modified cyclone behaves as though its cut is roughly 50% higher than the original. Preliminary calibration data taken since this program share roughly the same factor between the two cyclones.

SECTION IV

EGR TEST 1

SITE DESCRIPTION

The first field shakedown of the emission gas recycle system took place on June 8 through June 15, 1984. The source chosen was one of two twin 56 MW coal-fired boilers at a utility generating station. The plant normally operates at minimum (half) load; however, boiler load could be expected to increase as demand dictates. The exhausted combustion gas from each 56 MW unit is first directed through an American Standard electrostatic precipitator (located on the roof of the combustion facility) and then through a retrofitted, more efficient, Buell electrostatic precipitator. Finally, the two flue streams were manifolded together into a single stack. Since emissions are well controlled by the Buell ESP, the original ESP is activated but not well maintained. As shown in Figure 4-1, the sampling location was chosen as the outlet of the American Standard ESP on Unit 1.

The flow area of the sampling plane is approximately 132 square feet. Thirteen ports provide access to the duct interior: ten four-inch ports on the southeast side of the outlet duct and three six-inch ports on the southwest side. The ports are approximately 26 inches apart (see Figure 4-2). The geometry of the ductwork suggested velocity stratification, allowing for the testing of several recycle gas flowrates. The velocity distribution actually found, with boiler at half load, is shown in Figure 4-3. Because of the location of the sampling site (at the outlet of a relatively inefficient ESP), the particulate grain loading and mean particle size were expected to be somewhat larger than commonly found at well-controlled boilers. This would allow a good test of the PM_{10} performance, while avoiding undesirably lengthy run times.

TEST PROCEDURES

Subtest A: Colocated EGR/M17 Traverses

The test plan consisted of two subtests. Subtest A involved the comparison of traverses performed with the EGR train and a standard Method 17 (M17) train. To eliminate spatial bias, a probe was configured with a cyclone set (SoRI Cyclone I, Cyclone IV and a filter) using an EGR nozzle and a colocated 47mm filter (Method 17). The large diameter of this configuration required the installation of the three six-inch ports previously mentioned. Three traverse points were selected which represented the maximum point to point velocity change accessible to the EGR probe from the six-inch ports. The points chosen (labelled B1, B2, and B3 in test run sheets) were located 56, 36, and 16 inches, respectively, from the inside wall of port B (see Figure 4-4). The cyclone flowrate was selected to give a D_{50} of approximately 10 μm for Cyclone I by use of the original data of Smith et al. (1979). The recycle rate was then adjusted to achieve isokinetic sampling at each point while maintaining the chosen constant flowrate through the cyclone set. The flowrate through the colocated 47mm filter was adjusted at each point to sample

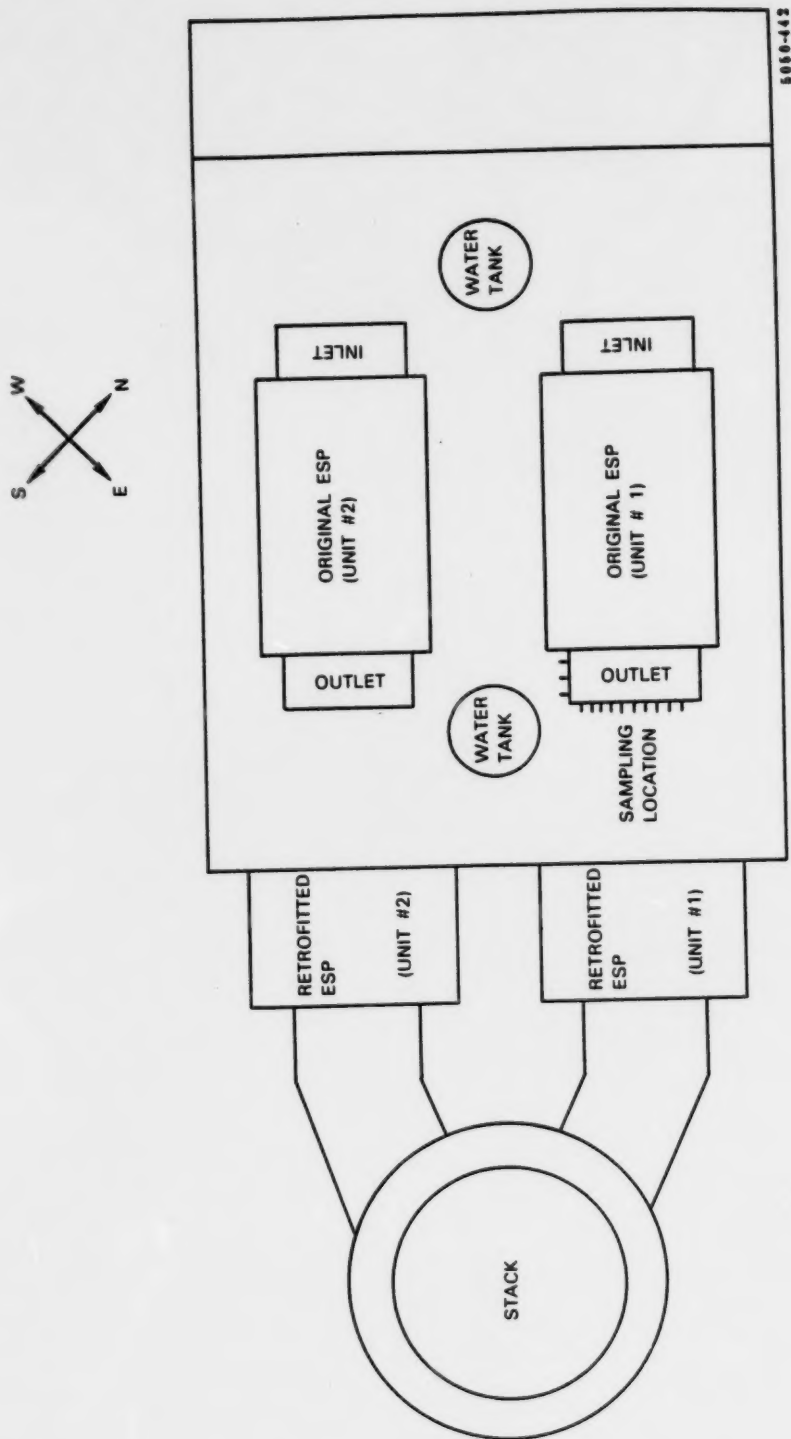


Figure 4-1. Plant layout.

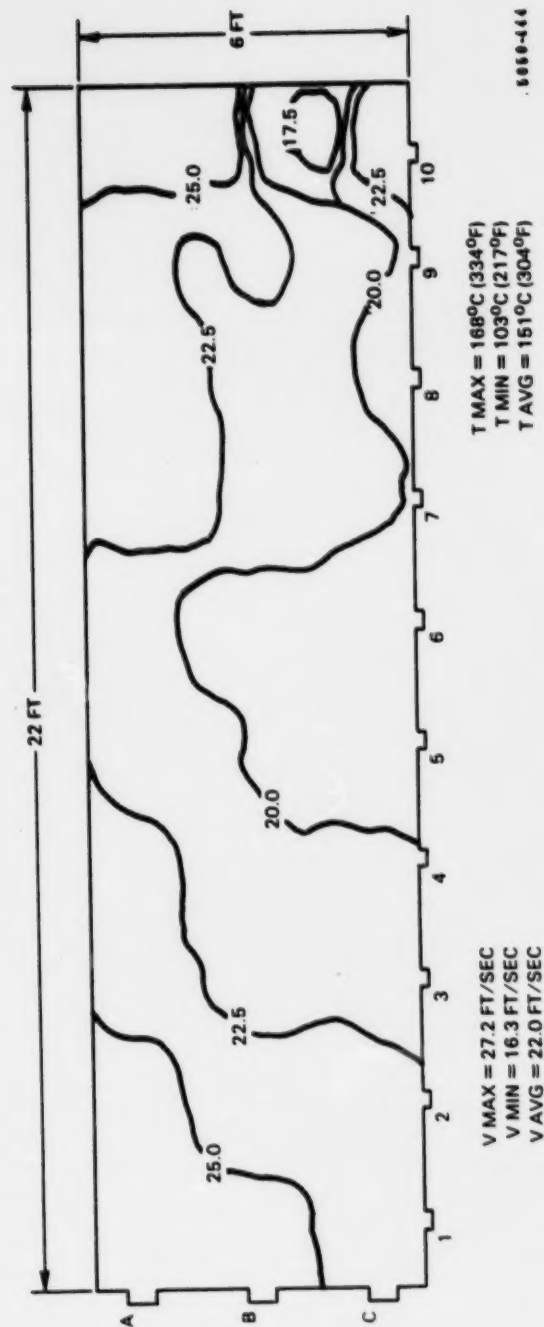


Figure 4-3. Sampling plane velocity traverse (with boiler at half load).

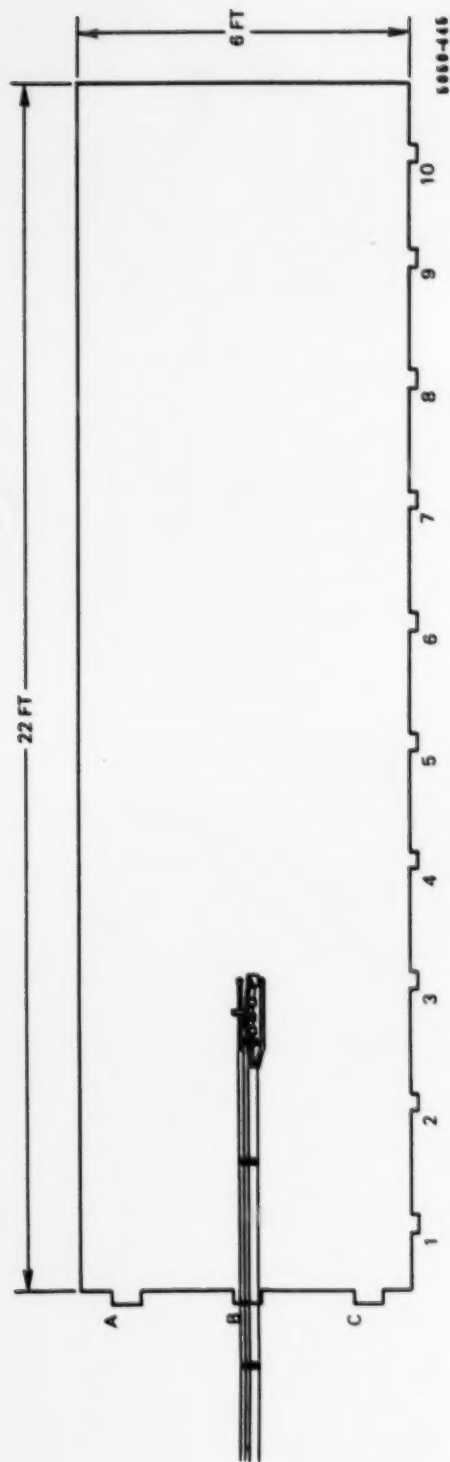


Figure 4-4. Subtest A: three point EGR/M17 traverses (pt. B-1 shown 56 in.).

isokinetically. Total particulate mass concentrations measured by the two trains were compared.

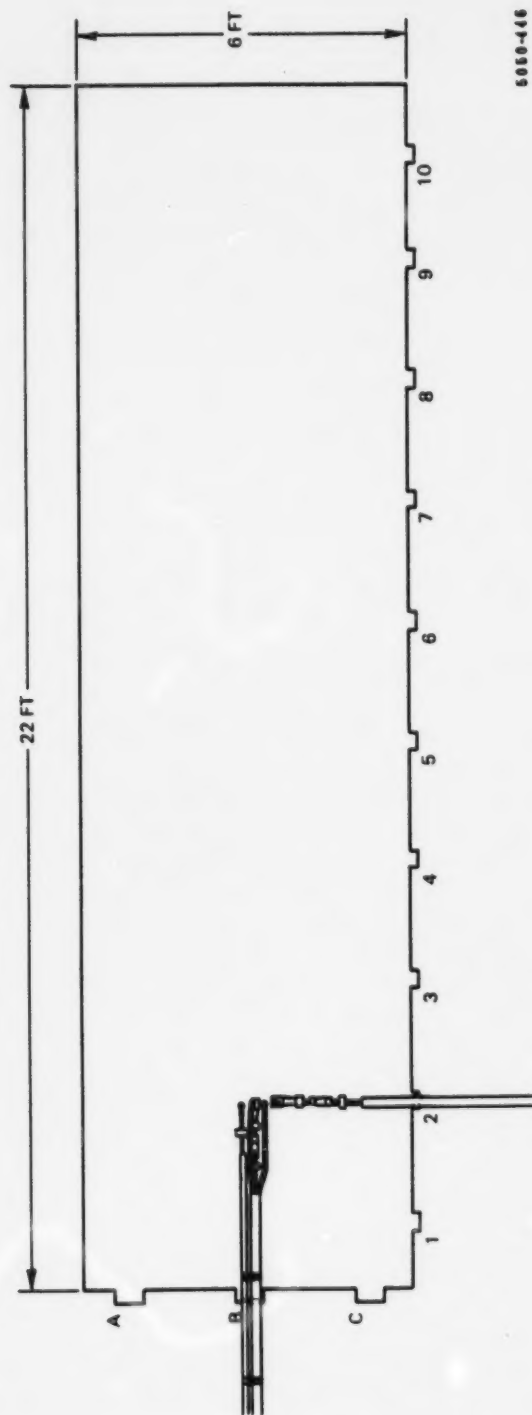
Subtest B: Simultaneous EGR/M17 and Non-Recycle Samples

In Subtest B, the EGR-M17 hardware described under Subtest A was used without modification. An additional non-recycle train was used for a "near-colocated" reference. This train used identical cyclone samplers equipped with a standard nozzle rather than the EGR nozzle. The remainder of the sampling train was conventional: a heated stainless steel probe, ice bath condenser, and a commercial Method 5 control box. Both probes (three sampling trains) were inserted at right angles in order to sample the same duct point (within approximately four-inch nozzle to nozzle spacing). Sampling for this subtest took place at the intersection of port B and port 2 (see Figure 4-5). All trains were made to sample at a nominally isokinetic rate, as follows. The duct point and nozzle for the non-recycle (STD) train were selected so that isokinetic flowrate was within 10% of the flowrate calculated for a $10 \mu\text{m } D_{50}$ in the cyclone. The isokinetic flowrate rather than the PM_{10} flowrate was used for sampling. The EGR cyclone was fitted with a smaller nozzle than the non-recycle train. The EGR sample flowrate was set to maintain isokinetic nozzle sampling. The recycle fraction was adjusted to make the cyclone flowrate identical to that used for the non-recycle cyclone. The gas flowrate in the Method 17 sampler was adjusted in the usual fashion to maintain isokinetic conditions. Total mass concentrations measured by all three trains and PM_{10} concentrations measured from the two cyclone trains were compared.

A total of ten EGR comparison runs were performed during the field shakedown test. The first run was aborted due to the collapse of the M17 sample line. In addition, both the EGR and M17 filters were found to be ruptured when unloaded. A large particulate loading found on the M17 filter suggested a reduction in either the M17 flowrate or the sample run time was necessary. It was decided to reduce the M17 flowrate by changing the nozzle diameter from 0.242 to 0.158 inches and keep the same run time. Also, to prevent future rupturing of filters, all sample lines were closed off whenever the probe was in the duct without the pump running. The second sampling run was completed, but a malfunction in the M17 control box caused that portion of the run to be at significantly higher than isokinetic flowrate. This M17 run was thus deleted from the test averages.

The remaining eight runs were completed successfully. Sampling runs 2 through 6 were port B traverses performed as described under Subtest A. With the exception of run 3, which occurred during a boiler load fluctuation (average ~34 MW), these tests were performed with the boiler at full load (56 MW). Runs 7 through 10 were replicates of Subtest B, all of which occurred at minimum boiler conditions (28 MW).

Six University of Washington Mark V impactors were run for comparison with the size distributions obtained by the two cyclone trains under Subtest B. The impactor configuration consisted of a right-angle precutter (Flow Sensor-type), stages 1, 2, 3, 4, 5, 7, 9, and a 47mm quartz-fiber backup filter. As with the cyclones and total mass train used under Subtest B, the impactors sampled at the intersection of port B and port 2. Two runs were obtained at full load



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Figure 4-5. Subtest B: single point comparison of EGR cyclones, standard cyclones, and M17 mass train.

boiler conditions, and four runs were obtained with the boiler at half load. At each boiler condition a "blank" impactor (UW1 & UW6) was run to determine the effect of stack gases on the collection substrates.

RESULTS

A chronology of the test is shown in Table 4-1. The run parameters and total mass loadings for Subtests A and B are shown in Table 4-2. As can be seen, the EGR was tested at a wide range of recycle rates (shown as percentage of the total flowrate). The data in Table 4-2 reflect one assumption made in post-test analysis. Post-test calibration checks revealed that the dry gas meter used for the standard (STD) cyclone train and the impactors was malfunctioning. It no longer maintained a reproducible calibration constant and was obviously outside the 5% post-test guideline. In an attempt to salvage data from the impactor and STD cyclone runs, total dry gas volumes were estimated using the sample time and dry gas flowrate as measured by the sampling orifice. We estimate from our calibration data that these calculated values of volume should be accurate to $\pm 5\%$. Comparison of these sample volumes with those obtained from the dry gas meter suggests that the dry gas meter had failed before any of the STD runs. Thus the data in Table 4-2 were calculated using the orifice flowrate and sample time measurements. The added measurement uncertainty should be taken into account when using these data.

Table 4-3 shows the comparisons of total mass loadings obtained under both subtests. As is shown, most of Subtest A was performed with the boiler at full load (56 MW); however, one run (Run 3) was performed at an intermediate boiler load of 34 MW. At full load, the Method 17 mass train indicated an average concentration of 2120.5 mg/dncm (reference temperature 68°F, pressure 29.92 in. Hg) with a 95% confidence interval of $\pm 30.1\%$. The colocated EGR cyclone train collected an average concentration of 1904.3 mg/dncm with a 95% confidence interval of $\pm 10.1\%$. At the intermediate boiler load the mass train and the EGR cyclones showed concentrations of 585.5 and 542.6 mg/dncm, respectively. In Subtest B the total mass concentrations at point 2B obtained with the M17, EGR, STD, and impactor trains averaged 74, 65, 57, and 71 mg/dncm with 95% confidence intervals of 27, 37, 21, and 8%, respectively. In both Subtest A and Subtest B, run-to-run variation because of process variation and random measurement error obscures or is substantially larger than differences or biases in the sampling techniques. Comparison on a paired basis for simultaneous samples is given below.

Tables 4-4 and 4-5 show the concentrations corresponding to each stage catch obtained from the UW impactors, EGR cyclones, and standard cyclones under Subtest B. In both tables, D_{50} refers to the aerodynamic particle diameter of the 50% "cutpoint" for each given sampler stage. The impactor data was reduced using a microcomputer version of a data reduction system for cascade impactors (McCain et al, 1979). The average impactor size distributions are plotted with the corresponding average cyclone results in Figures 4-6 and 4-7. Table 4-6 compares the cumulative loadings for the three size sampling systems.

The cumulative percent values for Cyclone I in Table 4-4 are particularly relevant to evaluation of the EGR technique. Ideally, differences in these values between the EGR and STD trains are the direct result of a difference in

Table 4-1. EGR Field "Shakedown" Test Chronology

Date	Tests
	(Subtest A)
Monday, 6-11-84	EGR(1)-M17(1)
Tuesday, 6-12-84	EGR(2)-M17(2)
	EGR(3)-M17(3)
Wednesday, 6-13-84	EGR(4)-M17(4)
	EGR(5)-M17(5)
	EGR(6)-M17(6)
	UW Impactor(1)
	UW Impactor(2)
	(Subtest B)
Thursday, 6-14-84	EGR(7)-M17(7)-STD(1)
	UW Impactor(3)
	EGR(8)-M17(8)-STD(2)
Friday, 6-15-84	UW Impactor(4)
	EGR(9)-M17(9)-STD(3)
	UW Impactor(5)
	EGR(10)-M17(10)-STD(4)
	UW Impactor(6)

Table 4-2. EGR Field Shakedown Run Parameters

	<u>Sample Flow (acfm)</u>	<u>Percent Recycle</u>	<u>Average Velocity (ft/sec)</u>	<u>Percent Isokinetic</u>	<u>Boiler Load (MW)</u>	<u>Mass Loading (mg/dncm)</u>
Run 1 ^a						
M17	0.8472	--		85.6		--
EGR	0.5912	13.2	48.8	101.2	56	--
Run 2						
M17	0.6746	--		164.3		1557.3 ^b
EGR	0.5581	18.0	47.5	98.1	56	2052.5
Run 3						
M17	0.5725	--		99.4		585.5
EGR	0.3295	59.6	27.6	96.8	34	542.6
Run 4						
M17	0.4030	--		96.1		2396.6
EGR	0.5868	15.6	46.7	100.9	56	1952.2
Run 5						
M17	0.4213	--		100.6		2077.2
EGR	0.6238	15.7	47.7	107.5	56	1804.2
Run 6						
M17	0.4777	--		107.7		1887.6
EGR	0.6422	9.6	49.8	104.5	56	1808.2
Run 7						
M17	0.4887	--		104.7		61.9
EGR	0.5662	20.8	22.6	105.9	28	42.9
STD ^c	0.6570	--		89.7		46.5
Run 8						
M17	0.4517	--		107.2		87.9
EGR	0.5253	41.6	20.2	108.8	28	75.7
STD ^c	0.6720	--		102.7		57.2
Run 9						
M17	0.4878	--		111.9		65.3
EGR	0.5540	33.6	21.1	111.0	28	63.9
STD ^c	0.7380	--		107.9		67.0
Run 10						
M17	0.4744	--		99.7		80.9
EGR	0.5555	34.9	22.8	101.9	28	74.5
STD ^c	0.7440	--		100.6		60.4
Impactors ^{c,d}						
UW2	0.5860	--	50.2	100.9	56	1380.0
UW3	0.4680	--	21.5	106.5	28	67.0
UW5	0.4540	--	21.4	103.7	28	72.8
UW6	0.4660	--	21.4	106.5	28	73.3

^aRuptured filters--run deleted from calculations.^bM17 control box malfunction--run deleted from test averages.^cFlowrates and gas volumes for all STD cyclone and impactor runs calculated using sample orifice rather than dry gas meter.^dRuns UW1 and UW4 were blank runs.

Table 4-3. Averages and Confidence Limits of
Total Mass Concentration

SUBTEST A

56 MW Boiler Load

	<u>Average Loading (mg/dncm)</u>	<u>Standard Deviation</u>	<u>95% Confidence Interval (Range)</u>	<u>Interval (Percent)</u>
M17 Mass Train (Runs 4, 5, 6)	2120.5	257.2 (12.1%)	1481.5-2759.5	±30.1%
EGR Cyclones (Runs 2, 4, 5, 6)	1904.3	120.4 (6.3%)	1712.7-2095.9	±10.1%
Impactor (Run UW2 only) ^a	1380.0	----	----	--

34 MW Boiler Load

M17 Mass Train (Run 3 only)	585.5	----	----	--
EGR Cyclones (Run 3 only)	542.6	----	----	--

SUBTEST B^a

28 MW Boiler Load

M17 Mass Train (Runs 7, 8, 9, 10)	74.0	12.4 (16.8%)	54.3-93.7	±26.7%
EGR Cyclones (Runs 7, 8, 9, 10)	64.2	15.2 (23.4%)	40.8-89.2	±37.2%
STD Cyclones (Runs 7, 8, 9, 10)	57.8	7.5 (13.2%)	45.1-68.9	±20.9%
Impactors (Runs UW 3, 5, 6)	71.0	3.5 (4.9%)	65.4-76.6	± 7.8%

^aNot traversed--sampled at point 2B only.

Table 4-4. EGR and Standard Cyclone Catches

	Isokinetic ^a	Total Concentration (mg/dncm)	Cyclone I			Difference of Cumulative Percent (EGR-STD)	Cyclone IV		
			D ₅₀ (μm)	Concentration Greater Than D ₅₀ (mg/dncm)	Cumulative Percent Less Than D ₅₀		D ₅₀ (μm)	Concentration of Cyclones I and IV	Cumulative Percent Less Than D ₅₀
EGR-Run 2	98.1	2052.5	10.6	1599.7	22.1	-	a	403.9	2.4
EGR-Run 3	96.8	542.6	10.1	429.4	20.9	-	a	94.2	3.5
EGR-Run 4	100.9	1952.2	9.4	1561.4	20.0	-	a	328.3	3.2
EGR-Run 5	107.5	1804.2	10.2	1393.0	22.8	-	a	344.1	3.7
EGR-Run 6	104.5	1808.2	9.9	1409.4	22.1	-	a	355.1	2.4
Run 7 EGR	105.9	42.9	9.27	25.1	41.5	1.7	a	11.9	13.8
STD	89.7	46.5	9.31	28.0	39.8		1.4	18.0	1.3
Run 8 EGR	108.8	75.7	8.66	53.9	28.8	-9.3	a	16.6	7.0
STD	102.7	57.2	9.25	35.4	38.1		1.4	18.5	5.7
Run 9 EGR	111.0	63.9	8.55	43.4	32.1	-10.8	a	14.7	9.1
STD	107.9	67.0	8.56	38.2	42.9		1.2	25.5	4.9
Run 10 EGR	101.9	74.5	8.61	46.7	37.3	-6.7	a	21.7	8.2
STD	100.6	60.4	8.63	33.8	44.0		1.2	24.3	1.6
						Average			
						Standard Deviation			
						95% Confidence Interval			

^aThe D₅₀ of modified Cyclone IV has not been characterized as discussed in Section III.

Table 4-5. Impactor Parameters and Results

	UW2	UW3	UW5	UW6
Flowrate (acfm)	0.5860	0.4680	0.4540	0.4660
Isokinetic Percent	100.9	106.5	103.7	106.5
Total Mass Loading (mg/dncm)	1380.0	67.7	73.2	68.4
Stage 1				
D ₅₀ (μm)	11.3	12.3	12.4	12.3
Loading (mg/dncm)	902.5	34.9	37.8	38.81
Stage 2				
D ₅₀ (μm)	5.4	5.9	5.9	5.9
Loading (mg/dncm)	351.2	6.62	7.82	10.3
Stage 3				
D ₅₀ (μm)	2.5	2.8	2.8	2.8
Loading (mg/dncm)	85.4	10.8	11.9	11.8
Stage 4				
D ₅₀ (μm)	1.4	1.6	1.6	1.6
Loading (mg/dncm)	36.6	9.84	10.9	3.76
Stage 5				
D ₅₀ (μm)	0.76	0.85	0.86	0.85
Loading (mg/dncm)	6.55	4.43	4.34	3.40
Stage 6				
D ₅₀ (μm)	0.41	0.47	0.48	0.47
Loading (mg/dncm)	0.91	1.09	0.25	0.24
Stage 7				
D ₅₀ (μm)	0.27			
Loading (mg/dncm)	0.30			
Filter				
Loading (mg/dncm)	2.29	0.12	0.12	0.12

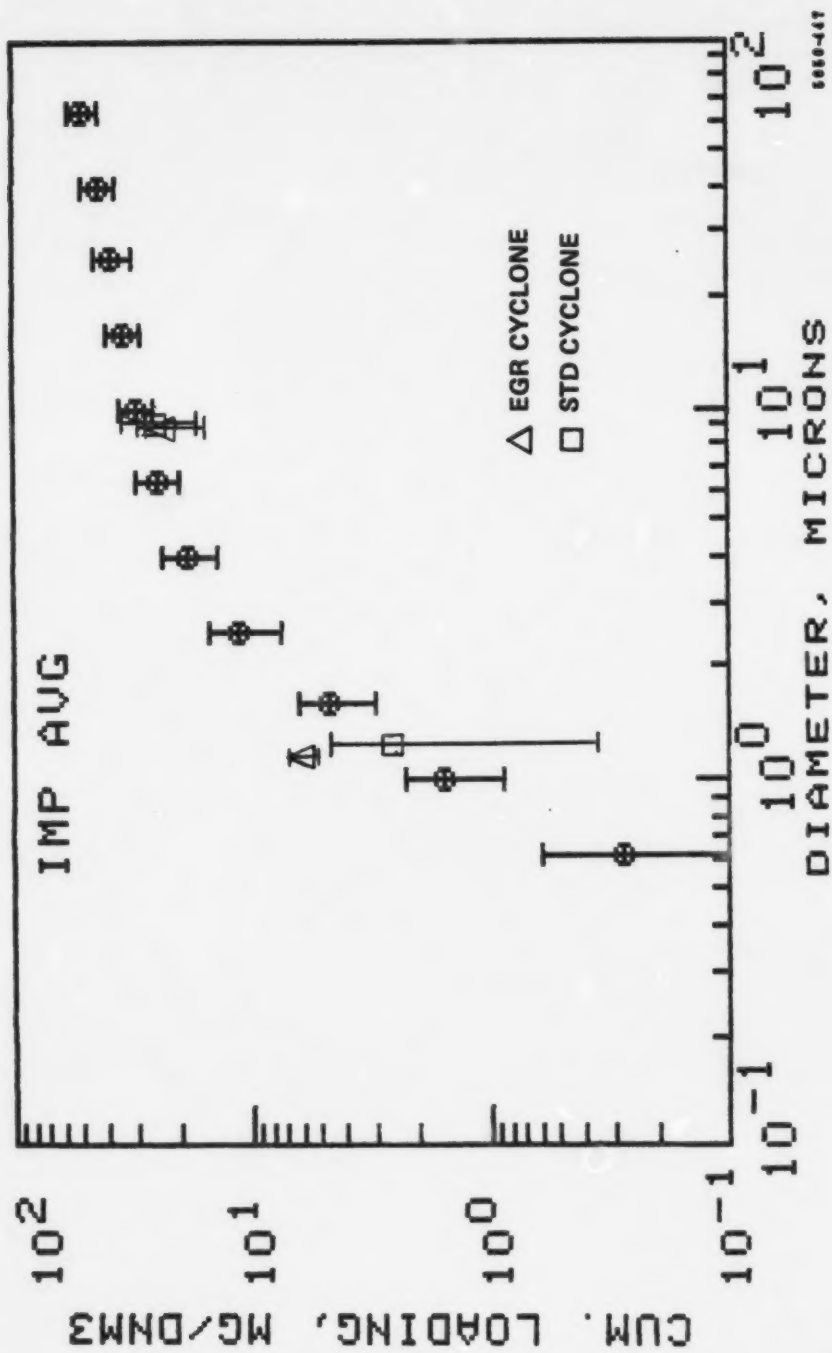


Figure 4-6. Particle size distribution data from Site 1 (cumulative mass basis).

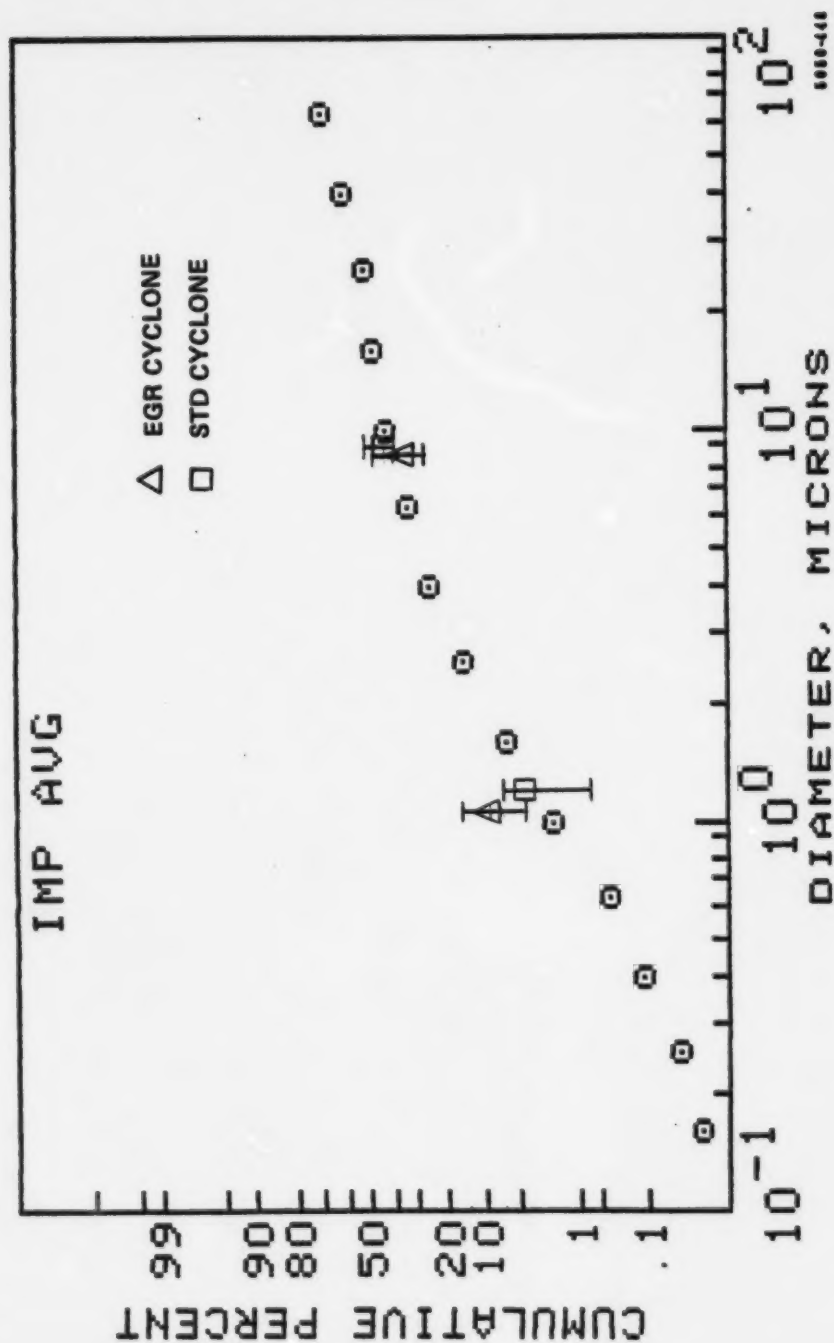


Figure 4-7. Particle size distribution data from Site 1 (cumulative percent basis).

Table 4-6. Summary of Size Distributions Data Obtained Under Subtest B

Cumulative Loading Less Than Cyclone D_{50}						
	D_{50} (μm)	(mg/dncm)	Standard Deviation	95% Confidence (Range)	Interval (Percent)	Cumulative Percent
^a Impactors (Runs UW3, 5, 6)	8.85	28.6	3.2 (11%)	20.6-36.6	±27.8	41.0
EGR Cyclones (Runs 7, 8, 9, 10)	8.8	22.0	4.2 (19.1%)	15.3-28.7	±30.4	33.8
STD Cyclones (Runs 7, 8, 9, 10)	8.9	23.9	4.7 (19.7%)	16.4-31.4	±31.3	41.9
^a Impactors (Runs UW3, 5, 6)	1.2	2.6	0.67 (25.8%)	0.94-4.3	±64.0	3.7
^b EGR Cyclones (Runs 7, 8, 9, 10)	(~1.8)	5.8	0.39 (6.7%)	5.18-6.42	±10.7	8.9
STD Cyclones (Runs 7, 8, 9, 10)	1.2	2.4	1.3 (55%)	0.33-4.47	±86.1	4.2

^a Impactor data interpolated from spline curve fit of actual data.

^b Best estimate of modified Cyclone IV D_{50} .

the size cut of Cyclone I due to differences between the standard and recycle nozzles. Note that indicated D_{50} is that calculated for Cyclone I as calibrated with a standard nozzle. The difference indicated by these data (average of -6.3%) is not significant at the 95% confidence level. The variation of data is due to random measurement error (such as error in recovering collected mass from cyclone surfaces and uncertainties in gas volume measurement due to malfunction in the dry gas meter used with the STD train) and random differences in the aerosols at the two sample points. The cyclone results agree with the impactor size distribution within the uncertainty due to run-to-run variations. These uncertainties are probably due to temporal variation of the process stream. Using the STD cyclone train as validation for the EGR system, it can be seen that the cumulative loading and cumulative frequency (see Table 4-5) of Cyclone I catches for both systems were not significantly different at the 95% confidence level. It can also be seen that the size fraction determined from Cyclone IV varied distinctly with each sampling train. The difference between the EGR and STD results for Cyclone IV is almost certainly due to the differences in geometry of the two versions of Cyclone IV as noted in Section III. The difference between the impactor and Cyclone IV (STD and EGR) data may be attributed to the lack of adequate calibration data to characterize the size cut of Cyclone IV at this viscosity.

Since the M17, EGR, and STD trains were operated simultaneously, analysis of differences in results of paired runs is the best method of resolving differences in these techniques. Effects of process variation are thus eliminated. The only remaining uncontrolled variables are then any concentration gradients which existed between sample points separated by four inches and any effects which the colocated probes may have had on the gas stream at the nozzles of the other probes. These are assumed to have been small. Table 4-7 gives percent error of total concentration for the EGR and STD sampling runs and the percent difference of total concentration and PM_{10} between the EGR and STD runs.

The EGR results show a negative bias of 11% relative to M17 with 95% confidence limits of $\pm 8\%$ while the STD results show a negative bias of 22% relative to M17 with 95% confidence limits of $\pm 22\%$. These differences are not explained by anisokinetic sampling error. The negative bias for both cyclone trains (EGR and STD) relative to M17 may be an indication of the lower sample recovery efficiency from cyclones; most of the PM_{10} particulate mass was deposited in the exit tube of Cyclone I, the inlet tube to Cyclone IV, and the Cyclone IV body. The highest percentage difference between EGR and M17 (-30.1%) occurred when the mass catch was only 16 mg (1/4 of the lowest of the other runs). The larger error for the STD train than for the EGR train was probably associated with the lower accuracy of gas volume determination due to gas meter malfunction with that train. This seems to be reflected by the higher standard deviations associated with the STD values.

Overall the EGR technique appeared to work well in this test. In comparison to Method 17 the differences were low and seemed to be associated more with the size separator than with the recycle nozzle itself. The accuracy of PM_{10} determination appeared to be good although the precision of the reference was not as good as desired.

Table 4-7. Comparison of Paired Runs

	Total			PM ₁₀
	<u>EGR-M17</u> <u>M17</u> <u>(%)</u>	<u>STD-M17</u> <u>M17</u> <u>(%)</u>	<u>EGR-STD</u> <u>Mean</u> <u>(%)</u>	<u>EGR-STD</u> <u>Mean</u> <u>(%)</u>
Run 3	-7.3	---	---	---
Run 4	-18.5	---	---	---
Run 5	-13.1	---	---	---
Run 6	-4.2	---	---	---
Run 7	-30.1	-24.9	-8.1	-3.9
Run 8	-13.9	-34.9	27.8	0.0
Run 9	2.6	-2.1	-4.7	-33.6
Run 10	-7.9	-25.3	20.9	4.4
Average	-11.5	-21.8	9.0	-8.3
Standard Deviation	9.9	13.9	18.0	17.2
95% Confidence Interval	±8.3	±22.2	±28.7	±27.4

SECTION V

SIM-5 TEST 1

SITE DESCRIPTION

The field shakedown of the SIM-5 sampling protocol took place on July 10 through July 16. The site chosen was the same 56 MW coal-fired boiler used for the EGR shakedown (see Section IV for a complete site description). This series of tests was performed with the boiler at a constant load of 28 MW.

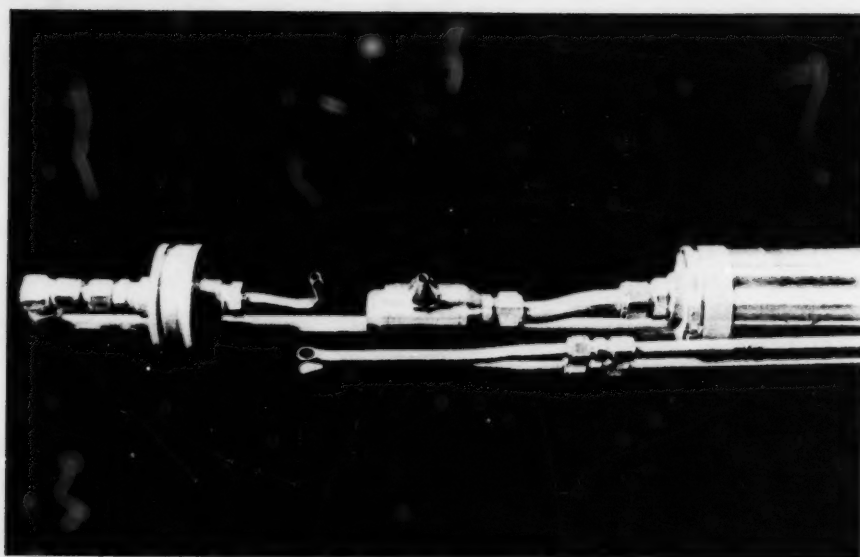
TEST PROCEDURES

The test plan consisted of three subtests. In all subtests the SIM-5 sizing devices were modified University of Washington Mark V (UW) cascade impactors. As mentioned in Section IV and described in some detail in Section VI, the impactors were configured with a Flow Sensor type right angle impactor precollector and six jet stages rather than the typical number for the Mark V impactor. The shorter impactor body used in the UW Mark III was used. Details on impactor configuration and data analysis were identical to those presented in Section VI.

Subtest A: Simultaneous SIM-5 and M17 Traverses

In Subtest A, two probes were used simultaneously to traverse the duct area. A Method 17 sampling nozzle and 63 mm filter were colocated with a University of Washington cascade impactor on one probe as shown in Figure 5-1. This probe performed a twelve point traverse of the duct area according to SIM-5 protocol with weighted sampling times at each point. The procedure for selecting the sampling times is described in more detail in Sections VI and VII. Total run time was 61 minutes. The traverse points are shown in Figure 5-2. The impactor was operated at a constant flowrate (SIM-5) while the flowrate through the 63 mm filter was changed so as to be isokinetic at each of the 12 traverse points. The second probe contained a 47 mm filter holder and was operated as a normal Method 17 sampling train using the 50 point traverse shown in Figure 5-2. The total run time was 50 minutes, one minute at each traverse point. Use of the colocated 63 mm filter on the SIM-5 probe gives determinations of total particulate mass from the 12 point SIM-5 traverse for comparison with total mass data using the standard M17 and SIM-5 impactor trains.

Three replicates of subtest A were completed successfully. The only problem was encountered with 25 minutes remaining in the third run when the boiler load began to increase. This took the pressure differential of the pitot off the range calculated for the operators use in setting ΔH on the Method 17 flowrate orifices so that linear approximations were necessary to determine the required orifice pressure drop. The results from the data reduction indicate this did not introduce significant error.



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Figure 5-1. Colocated 63 mm filter and UW impactor.

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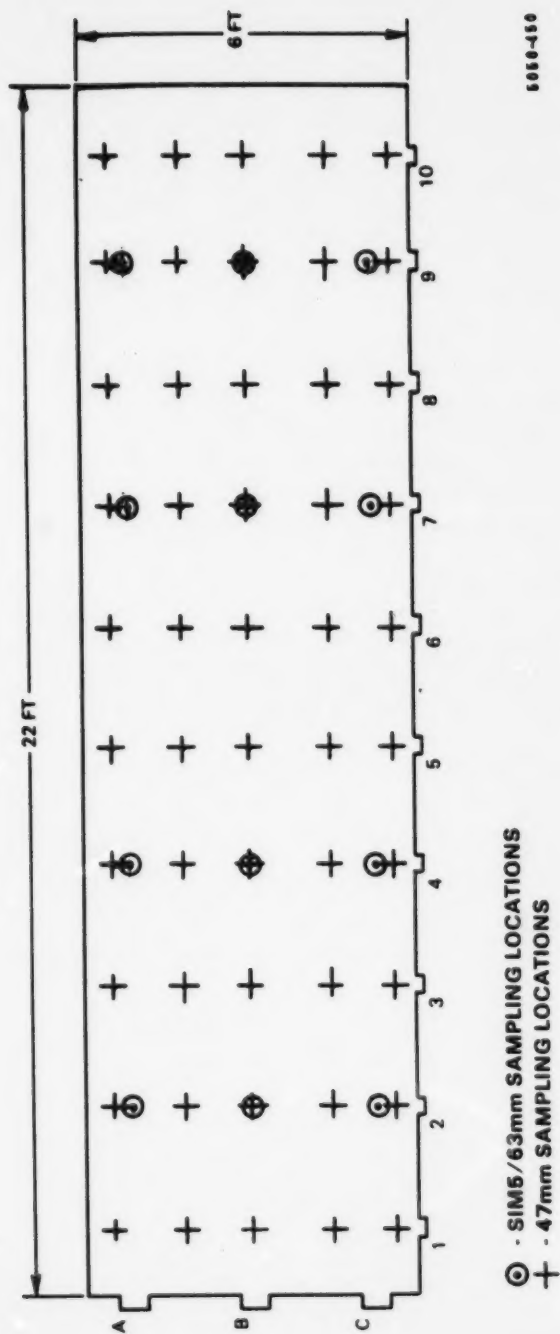


Figure 5-2. Subtest A: SIM-5-M17 traversing locations.

Subtest B: Three Colocated Impactors at Sub-, Super-, and Isokinetic Flowrates

For Subtest B, three identical impactors were run simultaneously at the same point (or nearly so) as illustrated in Figures 5-3 and 5-4. The ratio, R , of stream velocity to nozzle velocity for the three samplers was 0.6, 1, and 1.4, respectively. These values represent the limits specified by the SIM-5 protocol for this duct velocity of 8 m/sec at this point. Any differences in PM_{10} for these runs were expected to be due only to anisokinetic sampling and random variation of sampler behavior. The magnitude of error from isokinetic sampling relative to the latter is also of interest assuming that the aerosols at the 3 points (separated by 5") were identical. As described below, pitot measurements were made to see if any difference could be detected with and without every combination of the samples present. The impactors which sampled sub-, super-, and isokinetic were rotated to different points from replicate to replicate.

Subtest C: Three Single Point Impactors With One SIM-5 (Traversing) Impactor

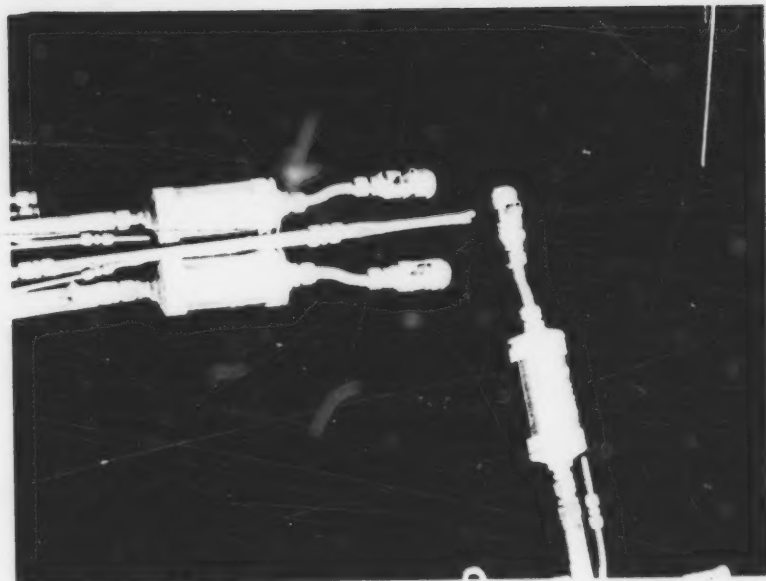
For the final subtest of the SIM-5 shakedown test series, three points in the sample plane were chosen with widely differing velocities. As illustrated in Figures 5-5 and 5-6, identical impactors with preseparators were operated simultaneously, one at each of these points, while another identical sampler traversed the same points in one sampling run according to the SIM-5 traversing procedure. The traversing impactor was operated for the same time period as the single point samplers but was colocated with the stationary sampler at each point for a time period proportional to the velocity at each point. The single point impactors sampled isokinetically. The three points sampled were 1A (intersection ports 1 & A), 3B (intersection ports 3 & B), and 5C (intersection 5 & C). The velocities, as determined by the reference pitot were 23.0, 19.8, and 17.6 ft/sec, respectively. The average from these three velocities is approximately 20.2 ft/sec.

PITOT COEFFICIENTS

Before any particulate sampling was performed in each subtest, pitot tubes were calibrated. This was not done in the SoRI wind tunnel because it was considered essential to calibrate each pitot mounted with the appropriate hardware. The colocated sampling configuration used for the three subtests made this impossible in the wind tunnel.

One pitot was calibrated before the test in the SoRI wind tunnel according to EPA Reference Method 2. On site, this pitot was used as a reference to calibrate the other pitots used during the test. An attempt was made to use a standard pitot on site, but the pressure differential was too low ($0.003'' H_2O$) at the point of maximum extension of the standard tube. Immediately prior to each of the on-site calibrations, each pitot and accompanying slant tube manometer was leak-checked as outlined in Method 2.

For each subtest, the reference pitot was inserted through port #2 to point 2B, and the pitot to be calibrated inserted to the same location through port B. In each case, care was taken to note whether the pitot readings were



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Figure 5-3. Three colocated UW impactors.

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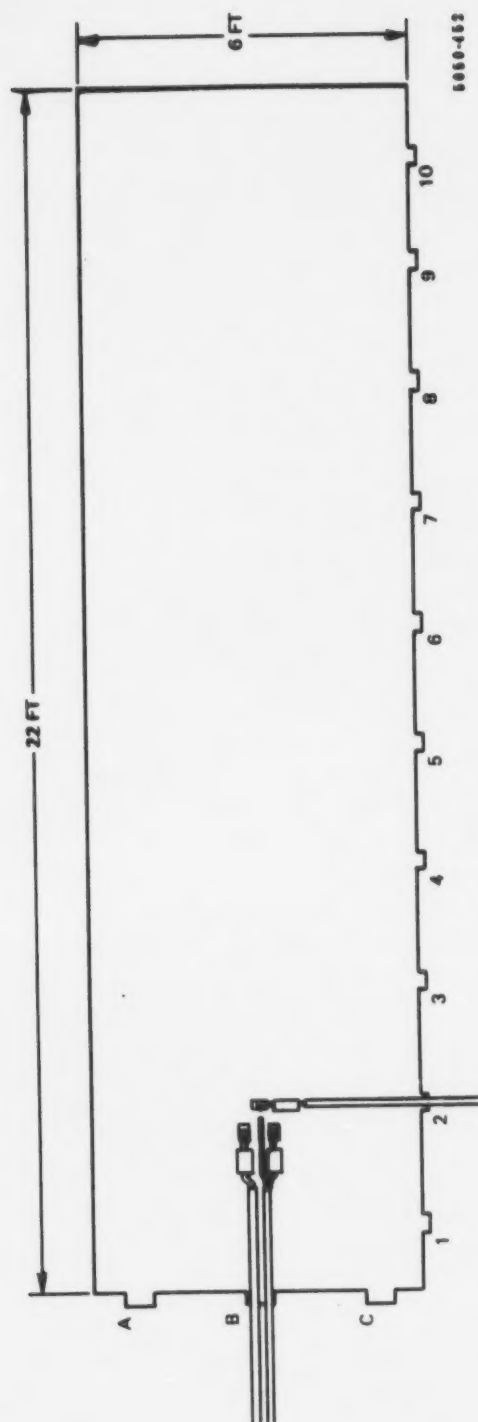
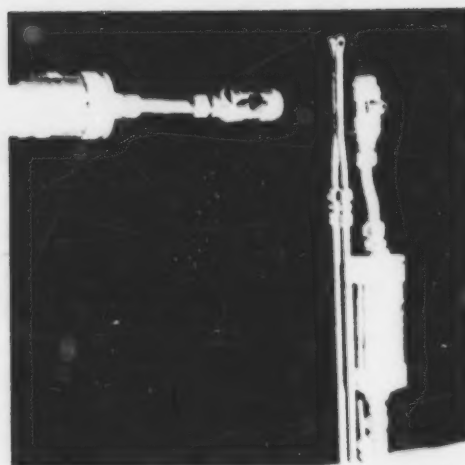


Figure 5-4. Subtest B: sampling location of three colocated impactors each run with a different isokinetic ratio.



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Figure 5-5. Single point impactor and traversing impactor colocated for subtest C.

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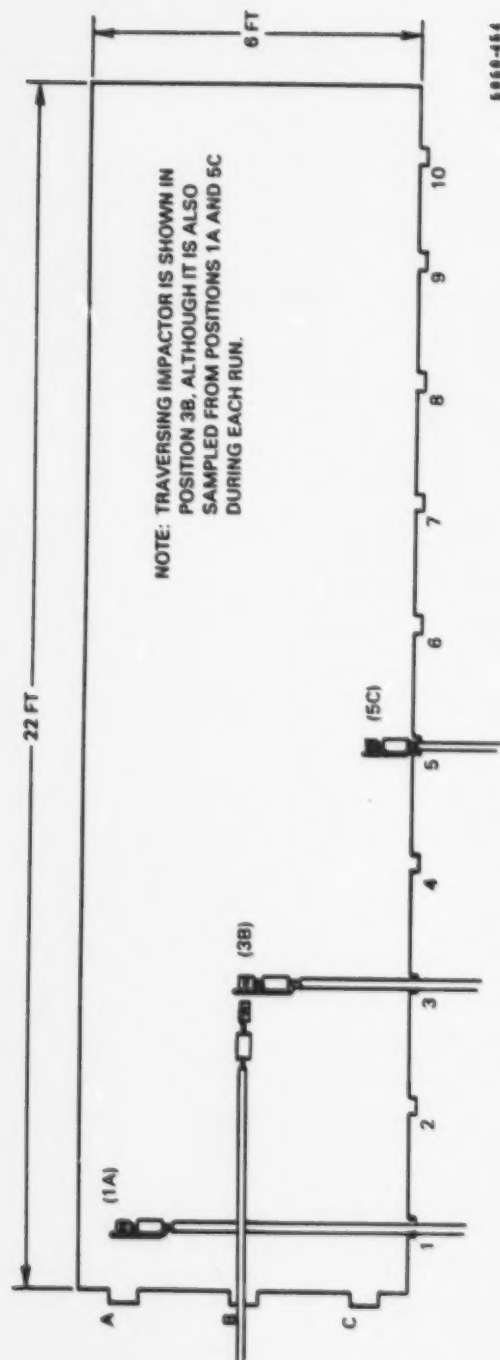


Figure 5-6. Subtest C: sampling positions of traversing impactor and simultaneous single-point impactor.

affected by moving the probes into and away from the proper sampling configuration. No such effect was seen.

TEST CHRONOLOGY

Table 5-1 gives the chronology of the three subtests.

RESULTS

Subtest A: Simultaneous SIM-5 Impactor and M17 Traverses

Table 5-2 shows the parameters of runs in this subtest. The nozzle velocity of the impactor runs was, of course, constant from point-to-point because of the constant impactor flowrate. In view of the fact that nozzle velocity was generally less than the gas stream velocities, the lower total concentrations measured with the SIM-5 impactors are somewhat surprising. Apparently factors other than anisokinetic sampling were involved. Perhaps the observed difference was associated with differences in sample recovery between the impactor and Method 17.

Table 5-3 summarizes the results of this subtest. It is interesting that the variation of PM_{10} was less than that of total concentration. As one might expect, the SIM-5 impactor agreed more nearly with the colocated M17 than with the Method 17 traverses at 50 points. The differences, not considered high, have not been explained.

Figures 5-7 give the average of the size distributions from the three impactor runs of this subtest. The calculated mass median diameters (MMD's) were 18.2, 26.3 and 31.6 μm , respectively.

Subtest B: Three Colocated Impactors at Sub-, Super-, and Isokinetic Flowrates

Table 5-4 presents parameters and results of impactor runs in Subtest B. As one might expect the measured concentrations increased as the percent isokinetic decreased, more so for total concentration than for PM_{10} . However, the correlation is not ideal, indicating the presence of other factors. To more clearly view the importance of the other factors the measured size distributions were corrected for errors due to anisokinetic sampling by calculating aspiration coefficient of 20 size increments by the equation of Belyaev and Levin (1974). Corrected, as well as measured, PM_{10} and total concentrations are given in Table 5-5. Also, coefficients of variation (COV's) of the sets of runs are given for measured and corrected results. It is seen that COV of total concentration is greatly reduced (from about 30 to 10%) when the variation due to anisokinetic sampling is removed. However, the COV of PM_{10} is not greatly affected by correcting for anisokinetic sampling; COV was increased in 2 sets and decreased in 2 sets. These results suggest that while anisokinetic sample error is quite important relative to other sources of uncertainty for total concentration, anisokinetic sampling error is obscured by other factors when measuring PM_{10} .

Table 5-1. Test 2 Chronology

Date	Test I.D.	Description
7/12/84	Subtest A-1 Subtest A-2 Subtest A-3	Colocated U.W. Impactor M17 Filter and M17 Traverse
7/13/84	Subtest B-1 Subtest B-2 Subtest B-3	Three Colocated U.W. Impactors
7/14/84	Subtest C-1 Subtest C-2	Three single point impactors with one traversing impactor
7/15/84	Subtest C-3 Subtest C-4 Subtest B-4	Three single point impactors with one traversing impactor Three colocated U.W. Impactors

Port/Point		A						B						C						Total Concentration
		Vn	Vs	Xiso	Td	Vn	Vs	Xiso	Td	Vn	Vs	Xiso	Td	Vn	Vs	Xiso	Td			
Isp Run 1	2	20.1	22.8	88.0	5.5	20.1	22.8	88.0	5.5	20.1	18.6	107.8	5.0							
	4	20.1	23.0	87.3	5.5	20.1	21.4	94.1	5.0	20.1	20.3	99.0	4.5							
	7	20.1	22.1	91.1	5.5	20.1	20.8	96.4	5.0	20.1	19.2	104.6	4.5							
	9	20.1	22.8	88.0	5.5	20.1	21.9	91.9	5.0	20.1	19.2	104.6	4.5							
Colocated	2	23.3	22.8	102.1	5.5	24.0	22.8	105.1	5.5	18.3	18.6	98.1	5.0					284.9		
M17 Run 1	4	23.9	23.0	103.7	5.5	21.9	21.4	102.6	5.0	20.4	20.3	100.5	4.5							
	7	22.6	22.1	102.5	5.5	21.3	20.8	102.2	5.0	19.4	19.2	100.8	4.5							
	9	23.7	22.8	103.6	5.5	22.4	21.9	102.4	5.0	20.0	19.2	104.3	4.5							
Isp Run 2	2	21.1	22.7	93.0	5.5	21.1	22.6	93.4	5.5	21.1	20.2	104.3	5.0					72		
	4	21.1	22.6	93.4	5.5	21.1	21.4	98.7	5.0	21.1	19.4	108.7	4.5							
	7	21.1	21.9	96.3	5.5	21.1	21.9	96.3	5.0	21.1	19.4	108.7	4.5							
	9	21.1	23.1	91.5	5.5	21.1	22.8	92.6	5.0	21.1	19.4	114.6	4.5							
Colocated	2	21.8	22.7	96.1	5.5	22.1	22.6	97.7	5.5	19.6	20.2	97.0	5.0					290.6		
M17 Run 2	4	21.9	22.6	97.1	5.5	20.9	21.4	97.8	5.0	18.8	19.4	96.9	4.5							
	7	21.3	21.9	97.5	5.5	21.3	21.9	97.1	5.0	18.8	19.4	96.9	4.5							
	9	22.3	23.1	96.7	5.5	21.9	22.8	96.1	5.0	18.2	18.4	98.9	4.5							
Isp Run 3	2	22.8	24.9	91.5	5.5	22.8	23.4	97.2	5.5	22.8	20.8	109.6	5.0					98.6		
	4	22.8	23.2	98.1	5.5	22.8	22.0	103.7	5.0	22.8	17.2	132.4	4.5							
	7	22.8	22.5	101.2	5.5	22.8	22.0	103.4	5.0	22.8	18.7	121.6	4.5							
	9	22.8	31.3	72.8	5.5	22.8	32.1	71.0	5.0	22.8	25.8	88.4	4.5							
Colocated	2	25.5	24.9	102.4	5.5	21.0	23.4	89.6	5.5	18.4	20.8	88.7	5.0					493.4		
M17 Run 3	4	20.5	23.2	88.3	5.5	20.5	22.0	93.2	5.0	19.8	17.2	114.8	4.5							
	7	20.1	22.5	89.3	5.5	19.8	22.0	89.7	5.0	16.7	18.7	89.3	4.5							
	9	28.6	31.3	91.4	5.5	29.2	32.1	90												

* V_N is nozzle velocity (ft./sec), V_S is stream velocity (ft./sec), Q_{SO} is percent isokinetic, and T_d is dwell time (sec) PM10 and Total Concentration are in $\mu\text{g}/\text{m}^3$.

Table 5-3. SIM-5 Shakedown Subtest A: Simultaneous
SIM-5 Impactor and Method 17 Traverses.

Method	Replications	Total Concentration mg/dncm	PM ₁₀ (mg/dncm)	95% Confidence Intervals (mg/dncm)
SIM-5 Impactor	3	310		±302
SIM-5 Impactor	3		84	± 33
Colocated M17	3	356		±295
Method 17	3	372		±415
Difference:				
Colocated M17 - SIM-5	3	46(13%)		± 42
M17 - SIM-5	3	61(16%)		±123

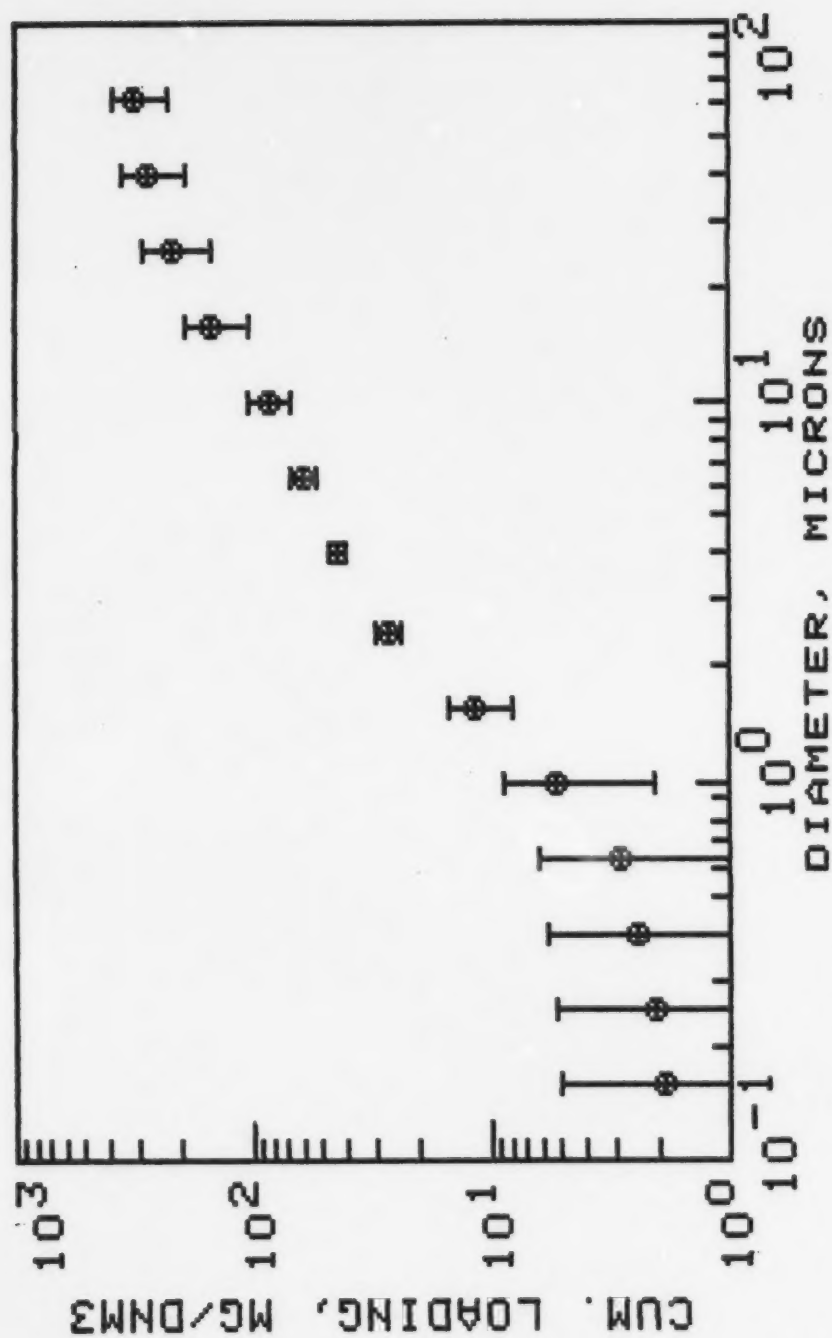


Figure 5-7. Average cumulative loading less than indicated size measured with SIM-5 Impactor traverses of the entire duct (12 points, Subtest A).

Table 5-4. Subtest B: Three Colocated Impactors^a

Point ID	2B				Total	
	Vn	Vs	% Iso	Td	PM10	Concentration
Imp Run 2-1	29.34	20.66	142.01	60	98.7	267
Imp Run 2-2	21.28	20.66	103.00	60	94.6	305
Imp Run 2-3	13.43	20.66	65.00	60	87.3	468
Imp Run 2-4	28.73	21.93	131.01	45	81.8	210
Imp Run 2-5	21.05	21.93	95.99	45	83.3	283
Imp Run 2-6	13.6	21.93	62.02	45	73.3	318
Imp Run 2-7	31.37	22.25	140.99	30	81.7	215
Imp Run 2-8	22.7	22.25	102.02	30	77.1	222
Imp Run 2-9	13.35	22.25	60.00	30	91.5	431
Imp Run 2-10	29.21	21.96	133.01	20	112	409
Imp Run 2-11	20.86	21.96	94.99	20	124	594
Imp Run 2-12	14.05	21.96	63.98	20	136	593
					Total	
					Concentration	
					Avg.	Std Dev.
Super-Isokinetic					93.6	14.7
Isokinetic					94.8	20.8
Sub-Isokinetic					97.0	27.0
					Avg.	Std Dev.
					275	93.8
					351	166
					452	113

^a Vn is nozzle velocity (ft/sec), Vs is gas stream velocity (ft/sec), %Iso is percent isokinetic and Td is dwell time (sec).

Table 5-5. Results of Subtest B Corrected for Anisokinetic Sampling.

	Concentration (mg/dncm) As Measured		Concentration (mg/dncm) As Corrected		Coefficient Variation As Measured (%)		Coefficient Variation As Corrected (%)	
	PM ₁₀	Total	PM ₁₀	Total	PM ₁₀	Total	PM ₁₀	Total
Impactor Run 2-1	98.7	267	105	316				
Impactor Run 2-2	94.6	305	95.0	310	6.2	30.8	11.8	6.0
Impactor Run 2-3	87.3	468	82.8	346				
Impactor Run 2-4	81.8	210	85.4	241				
Impactor Run 2-5	83.3	283	82.8	277	6.8	20.4	11.3	9.4
Impactor Run 2-6	73.3	318	68.8	233				
Impactor Run 2-7	81.7	215	86.1	257				
Impactor Run 2-8	77.1	222	77.2	224	8.8	42.4	5.8	15.9
Impactor Run 2-9	91.5	431	84.8	307				
Impactor Run 2-10	112	409	118	488				
Impactor Run 2-11	124	594	123	573	9.7	20.0	4.1	12.5
Impactor Run 2-12	136	593	128	450				

Figure 5-8 gives the average size distribution for each condition of this subtest.

Subtest C: Three Single Point Impactors With One SIM-5 (Traversing) Impactor

Table 5-6 presents parameters and results of impactor runs in Subtest C. Velocities at the three points sampled, 1A, 3B, and 5C, ranged from 16 to 25 ft/sec. At this low average stream velocity, this spread in velocity falls easily within the range of one nozzle for SIM-5 criteria. The total concentration was not obtained with the traversing impactor of the first set of runs due to a preweighing error of precollector substrate. This did not effect the particles less than 12 μ m in size. Total concentration varied widely with time and space. In particular point 1A had high levels of total concentration relative to the other points, with substantial temporal variation. Point 5C had the lowest concentrations with less temporal variation than point 1A and 3B. It appears that periods of high loading were intermittent at points 1A and, to a lesser extent, at point 3B, with the SIM-5 (traversing) impactor sampling such "bursts" of particles if they happened to occur at the right place and time. PM_{10} results indicate a similar pattern but to a substantially lesser extent.

Table 5-7 summarizes the results of these subtests. The observed difference between the SIM-5 impactor and the reference measurements with single point impactors was insignificant for PM_{10} . The SIM-5 impactors gave a higher PM_{10} fraction, 28% compared to 23%. Although this difference is not statistically significant at the 95% confidence level, one might expect the difference to be in this direction because the SIM-5 impactor flowrate was over-isokinetic on the average causing proportionately less of the large particles to be sampled. This mechanism, however, had insignificant effect on PM_{10} . Although the difference in total concentration between the SIM-5 impactor and single point impactors was not statistically significant at the 95% confidence level, it is also likely to be due to the over-isokinetic sampling by the SIM-5 impactor. However, the reader is cautioned that in general, total measured concentration may not always depend only on the average anisokinetic ratio, especially if spatial variation is severe and by chance the concentration is high when sampling over isokinetic and low when sampling under isokinetic.

Figure 5-9 presents the average size distributions for the SIM-5 and single point impactor traverses.

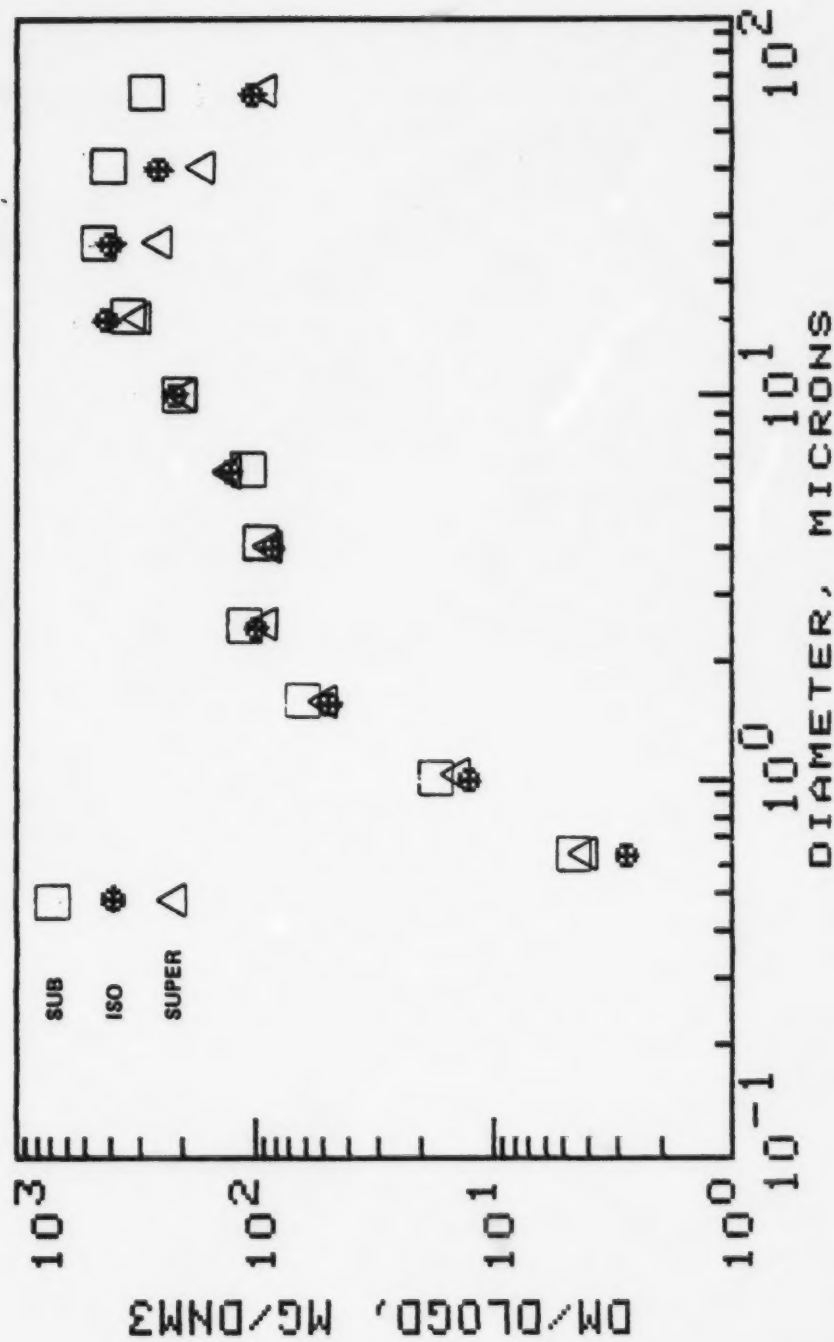


Figure 5-8. Average size distributions, DM/DLOGD versus LOGD, for Subtest B.

Table 5-6. Subtest C: Three Single Point Impactors With One SIM5 (Traversing) Impactors^a

Imp Run	3-1 trav	1A				3B				5C				PM10	Total Concentration ^a
		Vn	Vs	% Iso	Td	Vn	Vs	% Iso	Td	Vn	Vs	% Iso	Td		
-	3-1 (1A)	26.4	23.5	103.7	15	26.4	19.8	123.4	15	24.4	16.4	149.0	15	81.9	747
-	3-1 (3B)	22.6	23.5	96.0	45	18.6	19.8	94.0	45	16.9	16.4	103.0	45	95.8	498
-	3-1 (5C)													78.6	256
Imp Run	3-2 trav	18.9	22.5	83.7	10	18.9	19.6	96.1	10	18.9	15.6	121.1	10	72.4	200
	3-2 (1A)	21.4	22.5	95.0	30									93.5	336
	3-2 (3B)					18.8	19.6	96.0	30					80.4	243
-	3-2 (5C)									15.7	15.6	101.0	30	67.2	118
Imp Run	3-3 trav	23.6	25.3	93.0	12	23.6	21.9	107.5	10	23.6	18.0	131.2	8	141	920
	3-3 (1A)	26.6	25.3	105.0	30									137	1060
	3-3 (3B)					22.3	21.9	101.8	30					122	710
-	3-3 (5C)									19.9	18.0	111.0	30	101	317
Imp Run	3-4 trav	22.2	25.6	86.9	8.5	22.2	21.6	103.1	7	22.2	18.0	123.3	6	125	748
	3-4 (1A)	25.1	25.6	98.0	21.5									150	1510
	3-4 (3B)					20.5	21.6	95.0	21.5					130	920
-	3-4 (5C)									18.6	18.0	103.0	21.5	108	420

^a Vn is nozzle velocity (ft/sec), Vs is stream velocity (ft/sec), % Iso is percent isokinetic and Td is dwell time (sec).

^a Mass in precurter lost.

Table 5-7. Comparison of Particulate Concentrations Measured With A
SIM-5 Impactor and Single Point Isokinetic Impactors.

	<u>Number of Observations</u>	<u>Average</u>	<u>95% Confidence Limits</u>
<u>PM₁₀</u>			
Single Point Impactors	4	107	±36
SIM-5 Impactor	4	105	±53
Difference:			
Single Point - SIM-5 Impactor	4	1.8(2%)	±23(22%)
<u>PM₁₀ Fraction</u>			
Single Point Impactor	4	21%	±13%
SIM-5 Impactor	3	23%	±29%
Difference:			
Single Point - SIM-5 Impactor	3	-1.4%	±5%
<u>Total Mass</u>			
Single Point Impactors	4	623	±532
SIM-5 Impactor	3	623	±934
Difference:			
Single Point - SIM-5 Impactor	3	41(8%)	±548(65%)

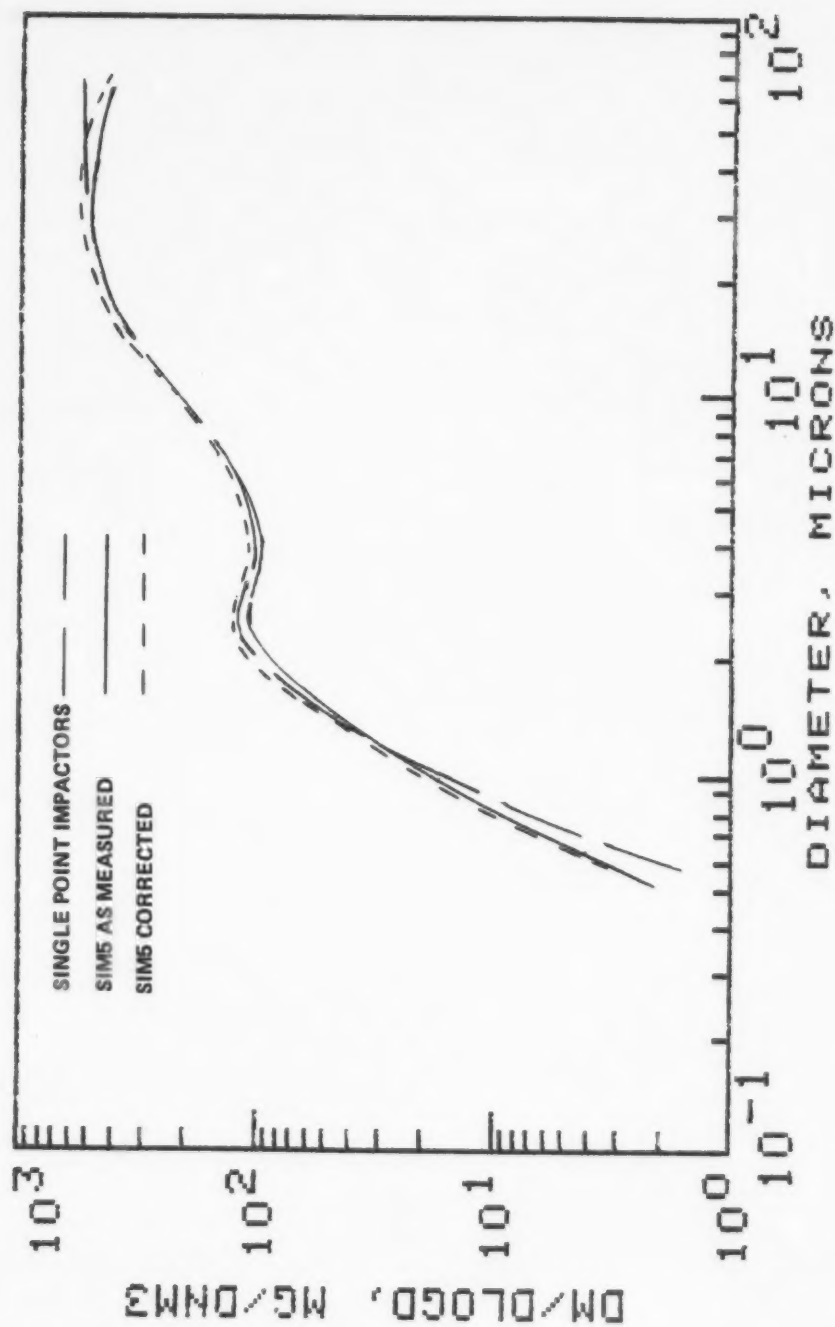


Figure 5-9. Average differential size distributions for Subtest C. Single point impactors and SIM-5 (traversing) impactors as measured and corrected for anisokinetic sampling error.

SECTION VI

EGR/SIM-5 TEST 2

SITE DESCRIPTION

This field test was performed on September 10 through September 15, 1984. The major purpose was to provide a direct comparison of the SIM-5 and EGR techniques. Independent reference measurements were obtained with single point isokinetic sampling. The site, a 500 MW coal-fired power plant, was selected to access a duct with velocities near 60 ft/sec, with substantial velocity spread, and with aerosol MMD in the 7-14 μ m range. This plant has two 250 MW units with each unit controlled by two cold side electrostatic precipitators (ESP's). Gas flow is horizontal through each of the four identical ESP's. The outlet duct of each ESP drops 25 ft to an ID fan. The outlet duct of each ID fan rises 35 ft to a right angle turn followed by a short run (~10 ft) into a common horizontal duct fed by all of the four ID fans. The four ID fans are situated in a row on the same side of the common duct which enters the base of the stack at one end. The outlet ductwork of each fan joins the common duct at a right angle. This field test was performed 25 ft above the outlet of the ID fan nearest the stack and 10 ft below its right angle turn leading to the common duct. Figure 6-1 is a photograph of the ductwork and sampling ports. The ID fan is to the lower left. The stack is to the right and eight ports used for sampling are at the upper center. These eight ports were designated A through H starting from left to right as viewed in Figure 6-1.

The velocity distribution for the sampling plane of this test, measured the first test day (9/10/84) is illustrated in Figure 6-2. The velocity is skewed to the West (right) side of the duct because this side is near the tangential exit from the ID fan. The cause of skew toward the Northeast (bottom left) side of the duct is not known. The average temperature of the duct was 284°F (ranging from 266 to 291°F).

TEST PROCEDURES

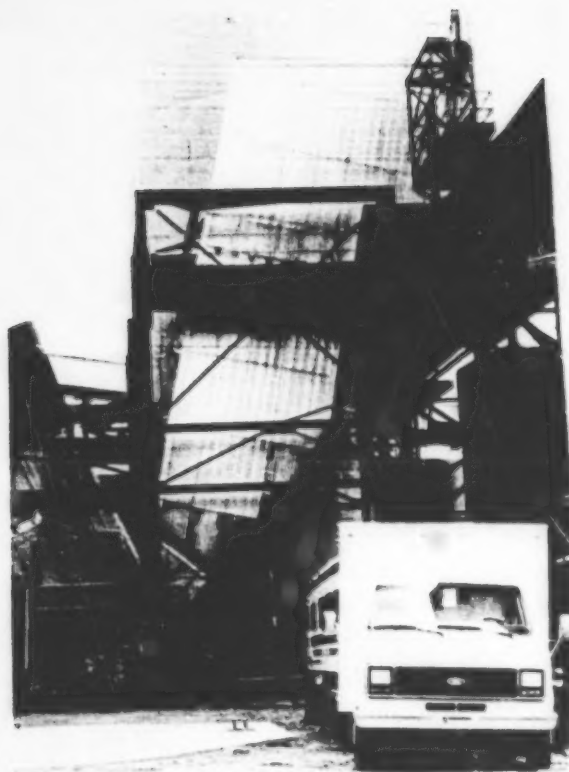
The test consisted of three subtests:

- A. Simultaneous three-point SIM-5 and EGR traverses using two PM₁₀ cyclone sampling trains.
- B. Three simultaneous isokinetic single point impactors, one at each of the traverse points used in Subtest A.
- C. Simultaneous SIM-5 and EGR traverses of 12 points using the same sampling trains as in Subtest A.

Subtest A: Simultaneous EGR/SIM-5 Traverses

Samplers--

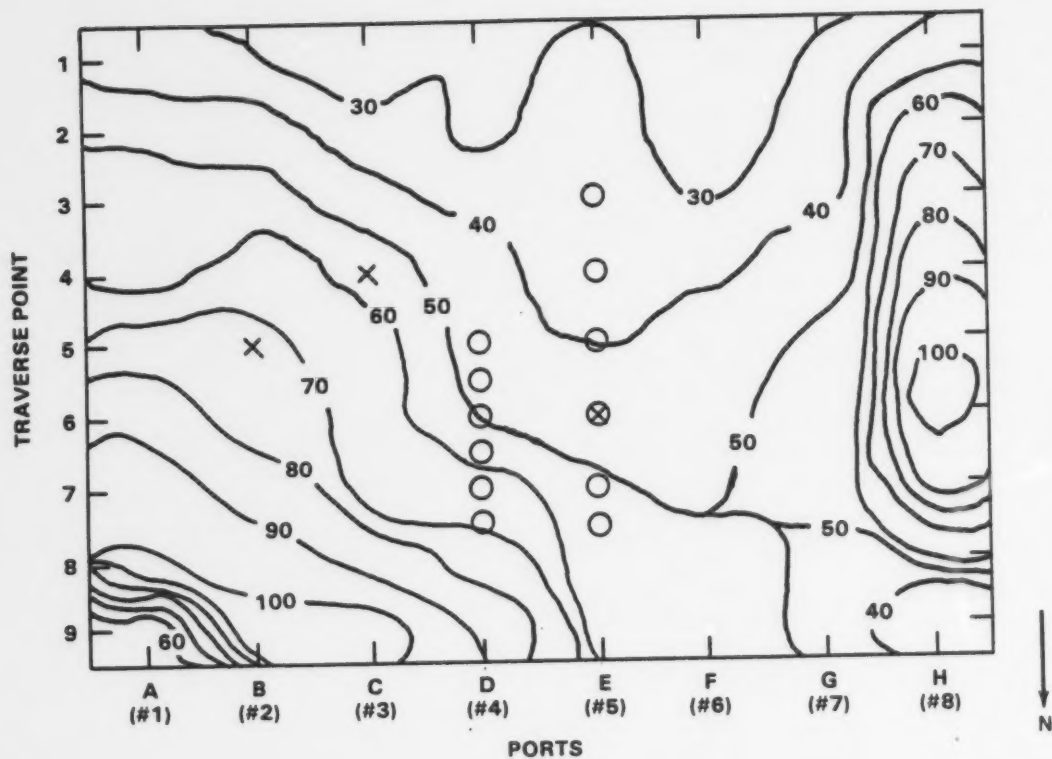
Identical PM₁₀ samplers were used for the EGR and SIM-5 sampling trains, the distinction being that the SIM-5 train has a standard nozzle instead of the EGR recycle nozzle. The PM₁₀ samplers for this subtest consisted of Cyclone I,



5050-455

Figure 6-1. Ductwork and sampling ports for SIM-5/EGR Test 2. The sampling ports are just above scaffolding at upper center of photograph.

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X'S INDICATE SAMPLE POINTS FOR SUBTEST A & B
O'S INDICATE SAMPLE POINTS FOR SUBTEST C

5050-456

Figure 6-2. Velocity profile of sample plane in SIM-5/EGR Test 2 (ft/sec). Sample points used in subtest A and B and subtest C are given.

Cyclone IV, and a 47mm filter holder in series as described in Section III. Each probe had an S-type pitot as required by the SIM-5 and EGR procedures.

PM₁₀ Flowrate--

The flowrate through both trains was set to produce a predicted 10 μ m aerodynamic D₅₀ for the first cyclone using equation 3-3.

Sampling points--

Three points were chosen for comparison runs of the SIM-5 and EGR techniques. The selection criteria were that velocities be low, medium, and high relative to the nozzle velocity of the SIM-5 sampler. The low and high velocity points were chosen to provide aspiration coefficients for 10 μ m particles near 0.8 and 1.2, respectively.

The choice of velocities was restricted by the combination of Cyclone I flowrate (0.6 acfm) and the smallest nozzle (0.18 in.) available for the non-recycle cyclone train. The medium velocity was chosen to be near the nozzle velocity, 58 ft/sec (17.7 m/sec). Determinations of the upper and lower velocity limits were accomplished on site using Figure 6-3. The procedure, outlined in Section III, was as follows: First the stack gas viscosity was determined for a gas composition of 9% O₂, 11.5% CO₂, 8% H₂O, and 71% N₂ at a temperature of 284°F. The O₂ and CO₂ values were obtained by Fyrites and the water content and temperature were obtained from a survey impactor run. Viscosity was obtained from results of the computer program used for impactor data reduction to be 217 micropoise. Thus, for a flowrate of 17.3 alp (0.6 acfm), $\mu/\bar{Q}$ used in Figure 6-3 was determined to be 1010. The maximum values of R and stream velocity, v, for the nozzle velocity of 17.7 m/sec were found to be 1.28 and 22.2 m/sec (73 ft/sec), at the intersection of the curve in Figure 6-3 passing through R=1 and the upper curve corresponding to $\mu/\bar{Q}=1010$. Similarly the minimum permitted values of R and v were found to be 0.68 and 12.2 m/sec (40 ft/sec). Based upon these limits, points B-5, C-4, and E-6 (see Figure 6-1) were chosen for this test.

Traversing procedure--

Both the SIM-5 and the EGR traverses were performed simultaneously but the probes could not be colocated in the four inch sampling ports. The EGR probe sampled the three points in the order E-6, C-4, and B-5 while the SIM-5 probe sampled C-4, B-5, and E-6. The EGR probe sampled at each point for 20 minutes while the dwell time for the SIM-5 probe was proportional to velocities at the points.

The variable dwell time for the SIM-5 probe was accomplished as follows. The first (medium velocity) point was sampled for 20 minutes, the average dwell time per point. During sampling of the first point pitot readings were recorded and the temporal average estimated to be ΔP_1 . Upon sampling at the second point, ΔP_2 was determined in the first 10 minutes and the dwell time calculated to be $t_2 = 20 \sqrt{\Delta P_2 / \Delta P_1}$ rounded to the nearest 30 seconds. The dwell time for the last point was calculated in the same manner as for the second point.

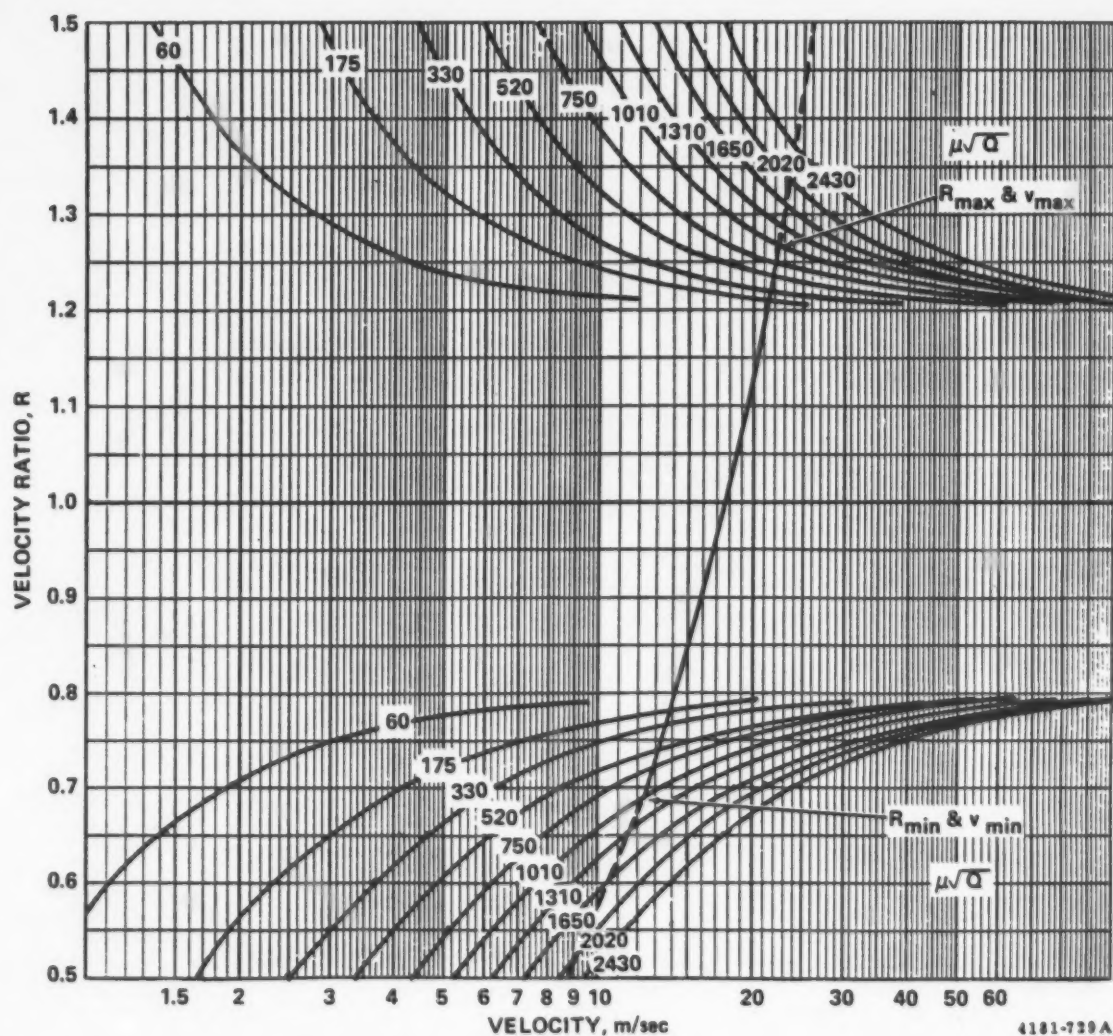


Figure 6-3. Velocity ratio R , duct velocity/nozzle velocity, versus duct velocity giving aspiration coefficient of 1.2 (upper curves) and 0.8 (lower curves) for particles with aerodynamic diameter of $10\ \mu\text{m}$ and gas viscosities ranging from 160 to 280 micropoise. Sampling error of $10\ \mu\text{m}$ particles is less than $\pm 20\%$ for R -values between an upper and a lower curve. $\mu\sqrt{Q}$ values are in micropoise $\sqrt{\text{alpm}}$. The curve passing through $R = 1$ is R versus v for a nozzle velocity of 17.7 m/sec.

While changing ports both the SIM-5 and EGR were shut down by simply clamping the sample and recycle lines before extracting the probes. The pump was kept running and valves left at their original positions. The nozzles were turned out of stream flow during extraction and reinsertion into the next port. Sampling was resumed by removing the clamp gradually. This duct was positive pressure so there was no concern with reverse flow disrupting the particulate deposits.

Subtest B: Simultaneous Single Point Impactors

Three University of Washington Mark V cascade impactors were run simultaneously as near in time as practical to each set of Subtest A (EGR/SIM-5). Each impactor was operated isokinetically at one of the three traverse points used for the EGR/SIM-5 subtest.

The geometry of the sampling probes was identical to the impactor probe with pitot shown in Figure 5-5. The precutter is manufactured by Flow Sensors Division of Andersen, Inc. Its size cut was determined from laboratory calibration work in EPA Contract 68-02-3118. In this configuration the jet diameter of the first stage of the impactor is the ID (0.5 inches) of the connecting tube between the precutter and the impactor. For the remaining impactor stages, jet plates can be selected with a variety of number and diameter of jets. Jet plates chosen for this test are designated 2, 3, 4, 5, 7, and 9 by the manufacturer (Pollution Control Systems). In this configuration impactor stages 1 and 2 have cutpoints larger than the precutter so particulate mass found on the stages was normally combined with the precutter catch.

Subtest C: Simultaneous 12 Point EGR/SIM-5 Traverse

An additional test was conducted to compare EGR and SIM-5 in a 12-point traverse and observe problems associated with a nozzle change during the SIM-5 run. Twelve points were chosen in two ports, indicated in Figure 6-1, with velocities satisfying the SIM-5 protocol for nozzle diameters of 0.18 (used in Subtest A) and 0.21 inches and a flowrate of 0.6 acfm for Cyclone I. Since this subtest addressed primarily the mechanics of nozzle changes, no attempt was made to traverse the entire duct. The nozzle velocity for the 0.21 inch was 43 ft/sec. The SIM-5 lower limits for R and v were 0.60 and 26 ft/sec and the upper limits were 1.32 and 55 ft/sec. These limits were determined from Figure 6-3 as in Subtest A. The 0.18 inch nozzle was used for sampling the six points in port D and the 0.21 inch nozzle was used for sampling the six points in Port E.

PRACTICAL PROBLEMS

Subtest A: Simultaneous EGR/SIM-5 Traverses

Eight replicates of Subtest A were initiated. In the first EGR run (EGR-1) there was difficulty with inserting the probe through the port without scraping the nozzle. At this point the nozzle was removed and repaired and Cyclone I cleaned to eliminate any scrapings. To help prevent scraping again,

a procedure was implemented using a sheath of galvanized steel (4" stove pipe). The sheath was inserted into the port before the probe. The sheath made a smooth clean tubular surface through which to pass the probe. Then after the probe was inserted the sheath could be pulled out and taken from around the probe. This process was reversed for removal of the EGR probe. Difficulty with inserting EGR-1 persisted; then it was recognized that the nozzle was not completely seated, causing it to protrude an extra 1/8". Tightening the nozzle eliminated the insertion problems. Use of the sheath during insertion and removal of the probe was continued throughout all EGR runs. While unloading Cyclone I after the first run small pieces of metal from the galvanized sheath were obvious, but it was concluded that these were scraped from the sheath before the nozzle was tightened. No fragments were visible in subsequent Cyclone I catches. In the final analysis it was concluded that these fragments affected the catch of Cyclone I only; i.e., the PM₁₀ data for this run was assumed valid.

Data from the second EGR run (EGR-2) was found void after the run due to reversal of the connectors of the sample and recycle lines at the probe exit. The possibility of this recurring has been eliminated by using different connector fittings for these two lines at the probe exit.

The fifth EGR/SIM-5 run was initiated but shortly thereafter the boiler load dropped from 240 to 190 MW due to plugging of a fuel feed line. This set of runs was aborted to expedite equipment turn around while boiler load was recovered.

Subtest B: Simultaneous Single Point Impactors

Seven replicates of Subtest B were performed, but points C-6 and B-7 were sampled during the first run instead of C-4 and B-5. The sampling points were changed after this replicate because a 1/8" nozzle (not available at the time of the test) for SIM-5 sampling would have been necessary at the 0.6 acfm flowrate. The impactor results at point E-6 in the first replication turned out to be an outlier when compared to the other replicates so it also was not utilized in final analysis of the data.

An open pitot line was found in the control box for the impactor at point B-5 prior to starting the second replication. This was indicated by condensation in the line. The problem was corrected prior to running the second impactor set. Two impactors had been run using this control box prior to this: a survey impactor and the low velocity impactor (point E-6) of the first impactor set. Examination of the stream velocities obtained during these two runs shows that the values recorded during the survey run agree well with a velocity traverse made earlier the same day. The same is not true of the first impactor run at point E-6. In an attempt to salvage the data from this run, a stream velocity was obtained by assuming the ratio of the velocities at this point for the velocity traverse and the first set of impactors was equal to the average of the same ratio at points C-6 and B-7. Data reduction for this run was performed using a stream velocity calculated in this manner. However, as mentioned previously, outlier analysis of the data resulted in the exclusion of this data from the final analysis.

Subtest C: Simultaneous 12 Point EGR/SIM-5 Traverses

These measurements were attempted only once. Shortly before sampling was initiated, boiler fuel line plugging problems returned. There was not time available for the sampling crew to wait until load was stabilized. During this subtest the boiler load was low (about 200 MW) with variations ± 10 MW as ramping upward was repeatedly attempted without success at bringing the boiler back to full load.

RESULTS

Table 6-1 shows the order and dates of performance of the various subtests.

Subtest A

Table 6-2 gives the parameters and results of Subtests A and B. For each traverse point, nozzle and stream velocities, % isokinetic, and dwell times are given for impactor, SIM-5, and EGR runs. The particulate concentration less than $10 \mu\text{m}$ (PM_{10}), total concentration, and PM_{10} fraction (ratio of PM_{10} /total) for impactor runs are given point-by-point. Also, since emission rate is the parameter of greatest interest, velocity weighted concentrations are given point-by-point for the impactor data.

At the bottom of Table 6-2 spatial averages for each subtest are given. Values for nozzle velocity and stream velocity are simple averages for the traverse. Under columns for impactors, a value for " PM_{10} " is given and a value for "Traverse PM_{10} ". The former is a simple average of the values for each impactor run in the set while the latter is the corresponding velocity weighted average. Corresponding values for total mass are given. The average PM_{10} fraction is the ratio of a velocity weighted average PM_{10} and total concentrations.

SIM-5 EGR Differences--

The differences between the SIM-5 and EGR for these tests, given at the bottom of Table 6-2, are of primary interest. For PM_{10} the SIM-5 technique averaged 15 mg/dncm higher than the EGR with 95% confidence limits of ± 6 . SIM-5 was also higher in total mass loading; the difference was 19 ± 18 mg/dncm. SIM-5 also gave a higher PM_{10} fraction although not statistically significant at 95% confidence; the difference was $3.3\% \pm 4\%$. These differences are analyzed further below.

Subtest B: Simultaneous Single Point Impactors

Figure 6-4 gives cumulative loading versus particle size for all impactor runs, excluding the first test. Ninety percent confidence limits are given, being relatively small, $\pm 4\%$ for sizes $> 10 \mu\text{m}$ increasing to $\pm 6\%$ at $2.5 \mu\text{m}$ and $\pm 15\%$ at $1 \mu\text{m}$. These confidence limits are for the simple average concentrations of the 18 runs. Of course individual runs varied more, from 135 to 275 for "total mass" and from 77 to 134 for " PM_{10} ". Figure 6-5 presents the average differential size distribution for all impactor runs. The larger 90%

Table 6-1. Test Chronology

Date	Run Codes
9/10/84	Survey Impactor Run (UW 40) Impactor 1-1, 2, & 3 (UW 41-43) ^a
9/11/84	EGR/SIM-5-1 ^b
9/12/84	Impactor 2-1, 2, & 3 (UW 44-46) EGR/SIM-5-2 ^c Impactor 3-1, 2, & 3 (UW 47-49) EGR/SIM-5-3 Impactor 4-1, 2, & 3 (UW 50-52)
9/13/84	EGR/SIM-5-4 Impactor 5-1, 2, & 3 (UW 53-55) EGR/SIM-5-5 ^d EGR/SIM-5-6 Impactor 6-1, 2, & 3 (UW 56-58) EGR/SIM5-7
9/14/84	EGR/SIM-5-8 Impactor 7-1, 2, & 3 (UW 59-61) EGR/SIM-5-12 pt. traverse Impactor blank (UW 62)

^a Traverse points changed after this set was run.

^b Total particulate concentration void in EGR run due to nozzle scraping. PM₁₀ concentration was valid.

^c EGR sample and recycle lines reversed.

^d EGR and SIM-5 runs aborted due to boiler load drop.

Table 6-2. Subtests A and B of SIM5/EGR Test 2 (Page 1 of 2).

Point I. D.	Time Segment(1)	Test 1			Test 2			Test 3			Test 4			Test 5 a		
		Iap	SIMS cye	EGR oyo	Iap	SIMS cye	EGR oyo	Iap	SIMS cye	EGR oyo	Iap	SIMS cye	EGR oyo	Iap	SIMS cye	EGR oyo
E-6 k-1	Nozzle Vel.	42.6	57.6	48.4	39.6	58.5	42.5	41.1	59.3	48.7	41.2	56.2	52.9	41.0	52.9	41.0
	Stream Vel.	52.9	43.1	47.1	41.3	44.7	42.0	39.9	40.8	45.5	38.5	42.3	46.1	39.2	46.1	39.2
	% Iso	80.5	134	103	95.9	131	113	103	145	107	107	133	115	105	133	115
	Drill Time	193	16.7	20	91.1	16.5	20	129	15	20	134	16	20	117	134	117
	Tot Mass	521			148			209			227			198	227	198
C-4 k-2	Weighted PM10				70.2			96.9			97.6			70.4	97.6	70.4
	Weighted Tot Mass				114			157			165			133	165	133
	PM10 Fraction				61.6			61.7			59.0			59.1	59.0	59.1
	Nozzle Vel.	55.3	57.6	79.8	53.7	58.5	61.7	54.6	59.3	61.7	57.7	56.2	63.8	62.3	57.7	63.8
	Stream Vel.	60.0	50.4	55.0	50.0	54.2	56.8	50.5	54.5	57.7	50.5	51.7	59.7	64.2	50.5	59.7
B-5 k-3	% Iso	92.2	114	145	107	108	109	108	109	107	114	109	107	97.0	109	107
	Drill Time	145	20	20	86.6	20	20	120	20	20	122	20	20	125	122	125
	Tot Mass	1110			197			215			275			258	275	258
	Weighted PM10				80.8			114			117			137	117	137
	Weighted Tot Mass				184			204			263			283	263	283
Spatial Averages	PM10 Fraction				44.0			55.8			44.4			48.4	44.4	48.4
	Nozzle Vel.	69.4	57.6	88.1	66.2	58.5	67.3	72.0	59.3	74.2	70.3	56.2	74.0	71.7	56.2	74.0
	Stream Vel.	77.3	66.6	72.9	69.5	69.4	65.7	69.0	66.4	72.1	69.5	66.1	71.3	72.0	66.1	71.3
	% Iso	86.8	86.5	121	95.3	84.2	102	104	89.4	103	101	85.0	104	99.6	85.0	104
	Drill Time	140	26.5	20	87.5	25.5	20	117	22	20	123	25	20	113	123	113
E-6 k-3	PM10	304			155			208			249			242	249	242
	Tot Mass				113			152			162			139	162	139
	Weighted PM10				201			270			328			298	328	298
	Weighted Tot Mass				56.5			56.3			49.4			46.7	49.4	46.7
	PM10 Fraction															
Spatial Averages	Nozzle Vel.	57.6	57.6	72.1	53.2	58.5	58.8	55.9	59.3	61.6	56.4	56.2	63.6	58.3	56.2	63.6
	Stream Vel.	55.3	55.3	58.3	53.6	57.9	54.8	53.1	55.5	58.4	52.8	55.1	59.0	58.5	55.1	59.0
	Run Time	63.2	60	60	88.4	62	60	122	97	60	126	61	60	118	126	118
	PM10				167			211			250			233	250	233
	Tot Mass															
Traverse PM10 SIM5-EGR Dif.	Traverse PM10	124	106	17.3	88.1	109	d	121	107	94.2	125	130	130	118	125	130
	SIMS-EGR Dif.									12.8			8.70			
	Traverse Tot Mass	264	c		166	213	d	210	201	195	252	307	279	238	252	307
	SIMS-EGR Dif.									6.70			28.9			
	PM10 Fraction															
PM10 Fraction SIM5-EGR Dif.	PM10 Fraction	46.9			53.0	51.0		57.5	53.1	48.4	49.8	45.0	46.6	49.7	45.0	46.6
	SIMS-EGR Dif.									6.75			-1.55			

a Velocities are in units of feet per second and concentrations in milligrams per dry normal cubic meter.

b Cyclone runs for this test aborted. Boiler going down.

c Inspector run not performed.

d Measured value was 948.1; this was high because of scraping inside of port.

e Measured values are 20.9 and 22.2 (PM10 and Tot Mass); recycle and sample lines were reversed.

Table 6-2. Subtests A and B of SIM5/EGR Test 2 (Page 2 of 2).

Test 6				Test 7				Test 8 b				Temporal Averages				Std. Deviation
Imp	SIMS	EGR		Imp	SIMS	EGR		Imp	SIMS	EGR		Imp	SIMS	EGR		
10	cyc	cyc	11	12	cyc	cyc	13	14	cyc	cyc	15	cyc	cyc	cyc		
42.2	57.2	49.0	42.5	56.9	53.6	53.3	53.3	58.9	53.3	53.3	53.3	39.7	42.7	45.7	102	
39.3	41.8	43.7	39.7	43.6	46.9	48.9	48.9	42.3	48.9	48.9	48.9	104	122	102		
107	137	112	107	130	114	109	109	139	109	109	109	106	122	102		
17	17	20	85.5	17	20	16	20	16	20	20	20	106.12				
80.1			149					177.67				177.67				
135			63.7					77.8				77.8				
60.0			111					130				130				
101			57.8					59.7				59.7				
59.3																
55.5	57.2	59.7	56.6	56.9	62.3	62.3	62.3	58.9	62.3	62.3	62.3	52.8	52.1	57.7	106	
50.7	49.2	56.2	50.0	52.2	59.2	59.2	59.2	52.7	59.2	59.2	59.2	108	103	106		
109	116	106	111	109	105	105	105	112	105	105	105	102				
20	20	20	83.4	20	20	20	20	20	20	20	20	205				
76.7			144					205				205				
143			79.7					100				100				
76.1			57.9					202				202				
138								50.7				50.7				
53.6																
66.8	57.2	68.2	71.0	56.9	71.3	71.3	71.3	58.9	71.3	71.3	71.3	69.5	67.5	69.1	101	
67.5	68.5	66.0	69.2	68.2	67.8	67.8	67.8	66.5	71.6	71.6	71.6	100	82.7	101		
99.0	83.5	103	103	83.5	105	105	105	88.6	104	104	104	101				
28	28	20	86.2	26	20	20	20	25.5	20	20	20	101				
77.3			183					192				192				
147			112					130				130				
99.4			56.3					247				247				
189								53.0				53.0				
52.6																
54.8	57.2	58.9	56.7	56.9	62.4	62.4	62.4	58.9	63.4	63.4	63.4	54.6	54.1	57.7		
52.5	55.6	55.3	55.3	56.5	58.0	58.0	58.0	55.7	60.0	60.0	60.0	103				
78.0	65	60	85.0	63	60	60	60	61.5	60	60	60	192				
142			149													
77.8	66.3	56.2	85.1	104	85.5	85.5	85.5	104	78.8	78.8	78.8	103	107	92.0	6.08	
	10.1	10.1			18.1	18.1	18.1		25.1	25.1	25.1			15.4		
143	130	115	149	207	200	200	200	228	189	189	189	193	221	196		
	15.2	15.2			7.20	7.20	7.20		39.0	39.0	39.0			19.4	14.2	
54.5	51.1	49.0	57.1	50.1	42.8	42.8	42.8	45.6	41.8	41.8	41.8	53.6	49.0	45.8		
	2.04	2.04			7.26	7.26	7.26		3.87	3.87	3.87			3.27	3.30	

SIMS-EGR Differences

Standard	d.f.
2.482	5
6.350	4
1.476	4

Traverse PM10
Traverse Tot Mass
PM10 Fraction

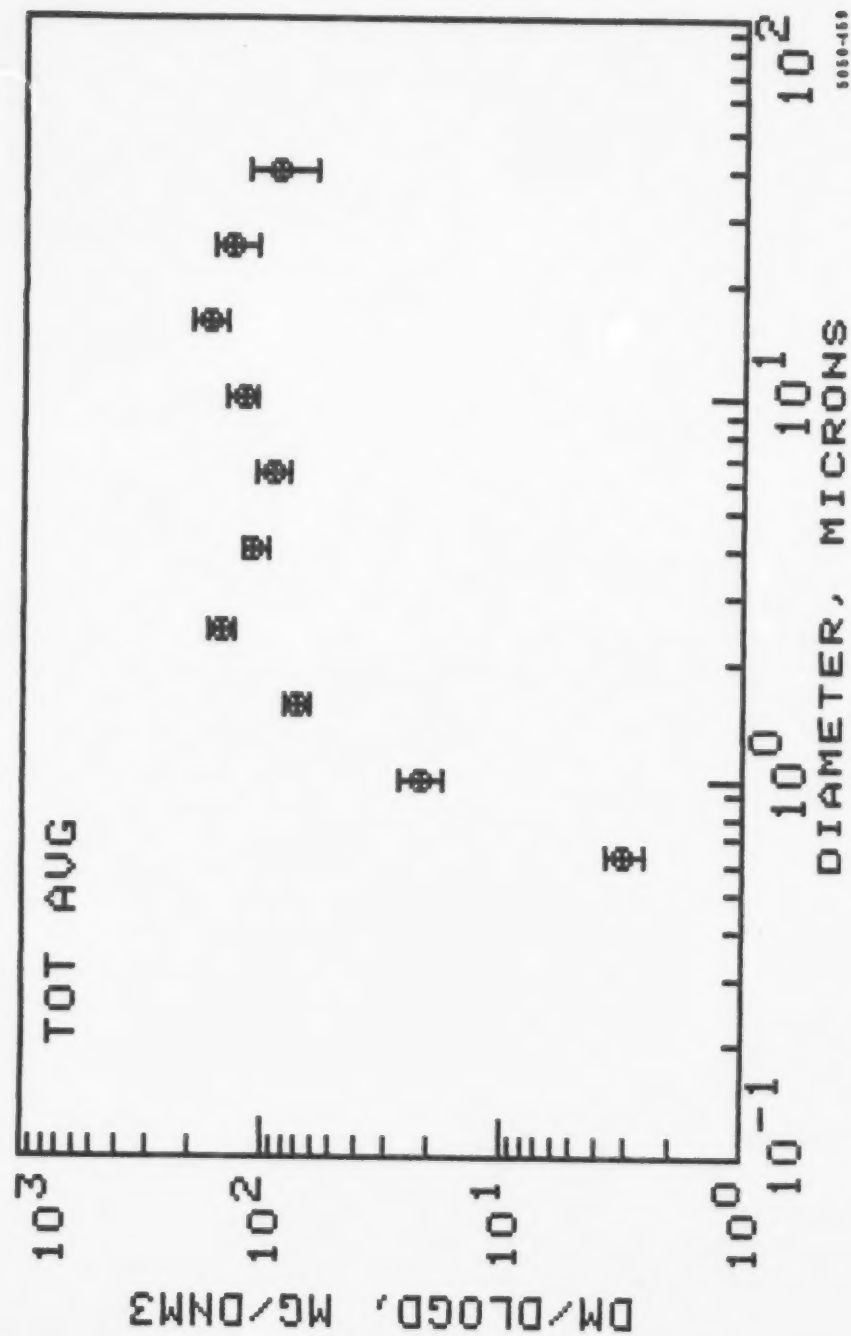


Figure 6-5. Average differential size distribution from impactors, EGR/SIM-5 Test 2.

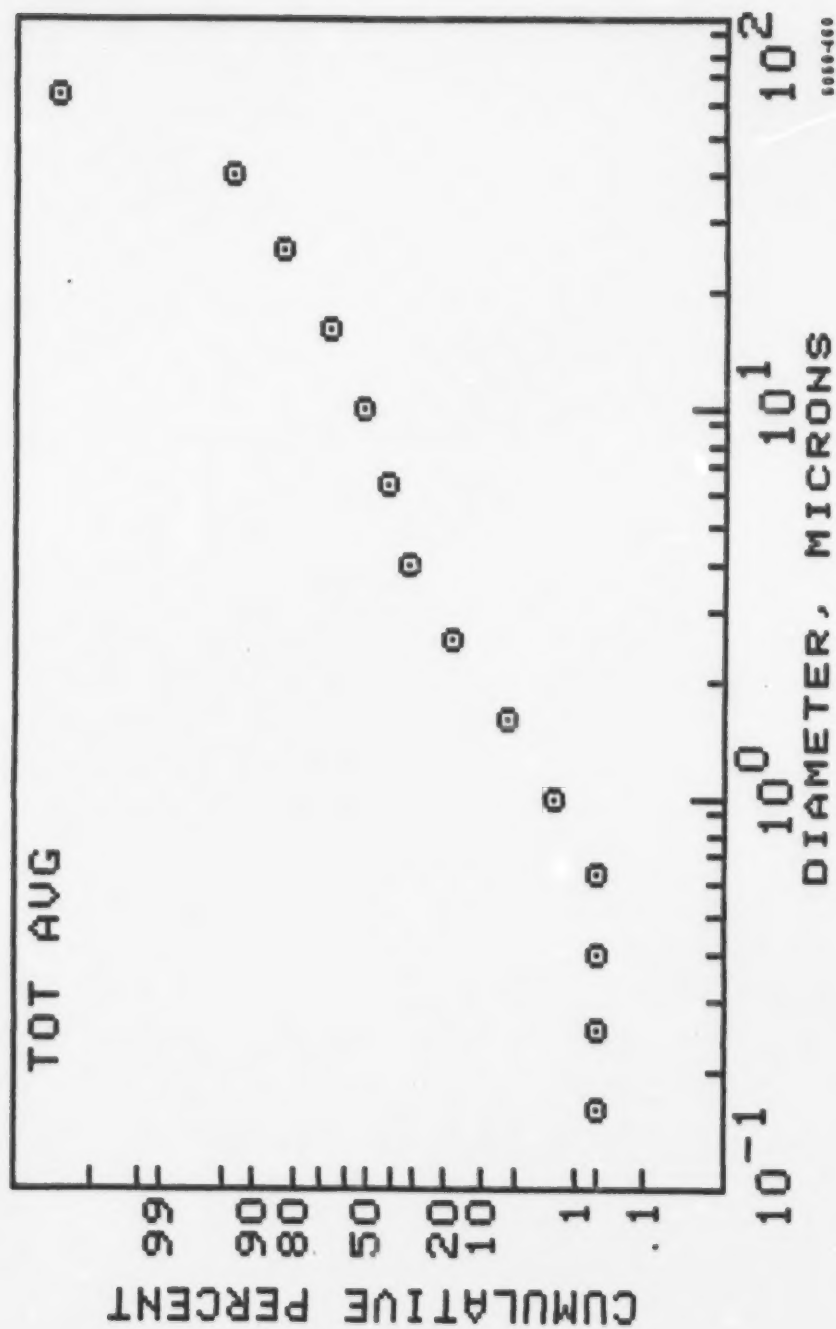


Figure 6-6. Average cumulative percent from impactors, EGR/SIM-5 Test 2.

confidence limits, relative to those in Figure 6-4, reflect variations between size bands that are irrelevant to cumulative loading. Figure 6-6 presents the average cumulative percent for all runs. The MMD was $10\mu\text{m}$. The quantities relevant to this study obtainable from the impactor runs are PM_{10} , total mass concentration, and the PM_{10} fraction. These values for each run are given in Table 6-2.

Subtest C: Simultaneous 12 Point EGR/SIM-5 Traverse

Table 6-3 gives the results of Subtest C. For each traverse point nozzle velocity, stream velocity, percent isokinetic and dwell times are given for the EGR and SIM-5 runs. The PM_{10} and total particulate concentrations are given at the bottom of this table. The SIM-5 and EGR agreed very closely in total mass (35.3 versus 35.5 mg/dncm). However the two techniques differed substantially in PM_{10} (26.3 versus 16.4 mg/dncm). The PM_{10} fraction measured with the EGR agrees with values observed in Subtest A while the SIM-5 value is high. These data suggest that particulate matter which should have been collected in Cyclone I on the SIM-5 probe penetrated to Cyclone IV. No mechanism for this occurrence is known. Inspection of the samples revealed nothing unusual. For both the EGR and SIM-5 samples, the Cyclone I catch was mostly black dust while the catch of Cyclone IV was light brown.

In view of the close agreement between EGR and SIM-5 in Subtest A and knowledge of boiler problems during this subtest, these results are not considered meaningful. Changing of the nozzle on the SIM-5 probe presented no obvious problems; however, a connection with the different PM_{10} values cannot be excluded.

ANALYSIS OF RESULTS

Correction for Anisokinetic Sampling

It is important to identify the cause(s) of the differences between the EGR and SIM-5 results shown in Table 6-2. To this end, corrections for anisokinetic sampling were calculated. The procedure followed for correcting EGR and SIM-5 results is described first.

SIM-5 measurements are expressed by

$$\bar{w} = \sum t_k w_k A_k / T$$

where $\bar{w}$ = measured average concentration, PM_{10} or total mass, for the three traverse points,

t_k = dwell time at the kth traverse point, chosen to be proportional to stream velocity at each point,

T = run time,

w_k = actual concentration at the kth, traverse point, and

A_k = aspiration coefficient averaged over the size distribution at the kth traverse point.

Table 6-3. Subtest C: Simultaneous SIM-5/EGR 12-Point Traverse

EGR				SIM5		
Port/Point		E	D	Port/Point	E	D
1	Nozzle Velocity	59.19	72.85	1	48.48	63.69
	Stream Velocity	61.78	76.66		54.57	67.65
	% Iso	95.81	95.03		88.84	94.15
	Dwell Time	5	5		7	8.5
2	Nozzle Velocity	55.07	65.77	2	48.48	63.69
	Stream Velocity	58.67	66.59		49.37	59.78
	% Iso	93.86	98.77		98.20	106.54
	Dwell Time	5	5		6	7.75
3	Nozzle Velocity	41.94	56.87	3	48.48	63.69
	Stream Velocity	44.52	60.54		38.29	53.03
	% Iso	94.20	93.94		126.61	120.10
	Dwell Time	5	5		5	6.75
4	Nozzle Velocity	31.32	50	4	48.48	63.69
	Stream Velocity	36.6	53.48		33.09	48.86
	% Iso	85.57	93.49		146.51	130.35
	Dwell Time	5	5		4.25	6
5	Nozzle Velocity	27.97	46.54	5	48.48	63.69
	Stream Velocity	30.92	49.42		29.34	42.76
	% Iso	90.46	94.17		165.24	148.95
	Dwell Time	5	5		3.75	5.5
6	Nozzle Velocity	26.21	41.71	6	48.48	63.69
	Stream Velocity	32.76	44.72		26.28	37.53
	% Iso	80.01	93.27		184.47	169.70
	Dwell Time	5	5		3.5	5
Averages						
Nozzle Velocity		48.0		56.6		
Stream Velocity		51.4		52.8		
Stream Velocity/Nozzle Velocity		1.09		0.923		
Run Time		60		63		
PM ₁₀		16.4		26.3		
Total Mass		35.5		35.3		
PM ₁₀ Fraction		46.2		74.5		

EGR measurements in this test are expressed by

$$\bar{\omega} = \sum u_k w_k A_k / 3\bar{u}$$

where u_k = nozzle velocity at the k th traverse point

$\bar{u}$ = average nozzle velocity for a traverse.

Dwell time in the SIM-5 and nozzle velocity in the EGR measurements were chosen to be proportional to stream velocity. Therefore, t_k/T and $u_k/3\bar{u}$ were the same weighting factors in both techniques except for small differences due to variations of the relative velocities between points during a pair of runs. An obvious source of differences between EGR and SIM-5 results is the differences in aspiration coefficients. To estimate these differences point-by-point average aspiration coefficients, A_k , for the EGR and SIM-5 runs were calculated from Equation 3-1 using the size distribution from the impactor measurements for the corresponding point and nearest in time.

Table 6-4 gives these average aspiration coefficients; "A(<10)" represents the coefficient calculated for all particles smaller than 10 microns, A(total) represents the coefficient for total mass loading, and "A(10)" represents the coefficient for 10 μ m particles. The latter is given for reference purposes only.

The aspiration coefficients for EGR results in Table 6-4 were obtained using corrected stream velocities. The correction was to reduce measured stream velocity by a factor of 0.94. The basis for this correction is that the stream velocities measured with the pitot on the EGR probe was consistently higher than those measured with pitots on the other probes. The average difference between the stream velocities measured with the SIM-5 and EGR probes was 3.65 ± 1.5 . Differences between stream velocities measured with the impactor and SIM-5 probes were found to be insignificant at 95% confidence.

The point-by-point aspiration coefficients in Table 6-4 were averaged. These averages, given at the bottom of Table 6-4, were calculated for SIM-5 by

$$\bar{A} = \sum t_k w_k A_k / \sum t_k w_k$$

and for EGR by

$$\bar{A} = \sum u_k w_k A_k / \sum u_k w_k$$

Since point-by-point concentrations, w_k , are not obtained in EGR or SIM-5 runs, these were approximated using the impactor results. SIM-5 and EGR results were corrected by dividing each value by its corresponding average aspiration coefficient. The difference between corrected SIM-5 and EGR was 12 ± 7 for PM_{10} , 8.3 ± 19 for total mass, and 4.3 ± 3.8 for PM_{10} fraction. Correction for anisokinetic sampling eliminated significant differences between SIM-5 and EGR measurements of total mass loading. However, there was apparently additional sources of difference in PM_{10} (or PM_{10} fraction).

Table 6-4. Subtests A and B of EGR/SIMS Test 2 with Corrections For Anisokinetic

Sampling Error (Page 1 of 2).

Point I. D.	Test 1 Imp 1	Test 1 SIMS cyc 2	Test 1 EGR cyc 2	Test 2 Imp 3	Test 2 SIMS cyc 4	Test 2 EGR cyc 4	Test 3 Imp 5	Test 3 SIMS cyc 6	Test 3 EGR cyc 6	Test 4 Imp 7	Test 4 SIMS cyc 8	Test 4 EGR cyc 8	Test 5 Imp 9
E-6 Time Segment(1) Nozzle Vel. Stream Vel. SIMS-EGR Diff. A(10) A(10) A(Tot)	42.57 52.9 1.167 1.080 1.16	57.6 43.14 -3.97 0.831 0.917 0.826	48.38 47.11 -3.97 0.938 0.971 0.966	39.6 41.3 1.030 1.010 1.02	58.48 44.65 0.840 0.931 0.872	47.54 41.97 2.68 0.874 0.945 0.898	41.1 39.9 0.982 0.992 0.986	59.32 46.81 0.791 0.910 0.835	49.71 45.5 -4.69 0.912 0.926 0.928	41.2 38.5 0.958 0.986 0.967	56.2 42.25 0.834 0.926 0.865	52.92 46.1 -3.85 0.866 0.940 0.890	41 39.2 0.972 0.992 0.978
C-4 k=2 Nozzle Vel. Stream Vel. SIMS-EGR Diff. A(10) A(10) A(Tot)	55.3 60 1.067 1.029 1.029	57.6 50.42 -6.58 0.912 0.972 0.917	79.8 55 -6.58 0.720 0.886 0.745	53.7 50 0.946 0.981 0.95	58.48 54.18 -2.57 0.947 0.983 0.95	61.66 56.75 -2.57 0.897 0.958 0.911	54.6 50.5 0.946 0.976 0.954	59.32 54.45 0.946 0.976 0.954	61.74 57.72 -3.27 0.911 0.957 0.926	57.7 50.5 0.901 0.961 0.916	56.2 51.72 -7.93 0.942 0.984 0.948	63.84 59.65 -7.93 0.907 0.957 0.919	62.3 64.2 1.025 1.016 1.020
B-5 k=3 Nozzle Vel. Stream Vel. SIMS-EGR Diff. A(10) A(10) A(Tot)	69.4 77.3 1.094 1.053 1.053	57.6 66.58 -6.32 1.116 1.04 1.08	88.1 72.9 -6.32 0.820 0.916 0.852	66.2 69.5 1.041 1.020 1.030	58.48 69.44 1.141 1.050 1.100	67.34 65.73 3.71 0.942 0.973 0.946	72 69 0.964 0.983 0.973	59.32 66.37 1.089 1.040 1.060	74.22 72.11 -8.74 0.933 0.964 0.946	70.3 69.5 0.994 1.000 0.992	56.2 66.1 -5.2 1.131 1.050 1.100	74 71.3 -5.2 0.928 0.950 0.938	71.7 72 1.003 1.009 1.003
Spatial Averages													
Nozzle Vel.	57.60	72.09	88.1	53.17	58.48	58.95	55.90	59.32	61.56	56.40	58.20	63.59	59.33
Stream Vel.	55.27	58.34	72.9	53.60	57.92	54.82	53.13	55.46	58.44	52.83	55.13	59.02	58.47
SIMS-EGR Diff.	-4.96	-4.96	-6.32	1.27	1.27	1.27	1.27	1.27	-4.67	1.27	1.27	-5.66	1.27
Traverse PM10	123.50	106.20	88.14	88.14	108.50	93.46	120.95	107.00	94.20	125.35	138.40	129.70	118.29
Traverse Tot Mass	263.60	244.20	166.26	166.26	212.80	193.40	210.47	201.40	194.70	251.94	307.40	278.50	238.02
PM10 Fraction	46.851	43.489	53.016	53.016	50.987	48.325	57.469	53.128	48.382	49.755	45.023	46.571	49.695
Avg. A(10)	0.996	0.920	0.909	1.009	0.967	0.909	0.966	0.960	0.922	0.963	0.991	0.905	1.004
Avg. A(10)	0.985	0.918	0.918	1.005	0.965	0.961	0.985	0.983	0.960	0.984	0.994	0.956	1.008
Avg. A(Total)	0.959	0.844	0.844	1.000	0.973	0.922	0.973	0.964	0.934	0.962	0.990	0.919	1.004
Corrected Traverse PM10	125.4	115.7	87.7	122.8	108.9	98.1	122.8	108.9	98.1	127.4	139.2	135.7	117.3
SIMS-EGR diff.	274.9	9.69	166.3	166.3	208.9	208.5	216.3	208.9	208.5	261.9	310.5	303.0	237.1
Corrected Traverse Tot Mass	45.6	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8
SIMS-EGR diff.	45.6	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8
Corrected PM10 Fraction	45.6	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8
SIMS-EGR diff.	45.6	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8

a Cyclone runs for this test aborted. Boiler going down.
c Measured value was 948.1; this was high because of scraping inside of port.
Refer to test for source of value given.

Table 6-4, Continued (Page 2 of 2)

Point I. D.	Time Segment(I)	Test 6			Test 7			Test 8			Temporal Averages			Port Averages	Std. Deviation
		Inp	SIMS eye	EGR eye	Inp	SIMS eye	EGR eye	SIMS eye	EGR eye	Inp	SIMS eye	EGR eye			
E-6 k=1	Nozzle Vel.	42.2	57.2	49	42.5	56.91	53.59	58.92	53.31	39.65	42.66	45.74	42.68	2.57	
	Stream Vel.	39.3	41.79	43.71	39.7	43.62	46.88	42.33	48.9						
	SIMS-EGR Diff.			-1.92			-3.26		-6.57						
	At (10)	0.959	0.922	0.903	0.955	0.941	0.967	0.910	0.897		0.976	0.924	0.931		
	At (10)	0.984	0.925	0.948	0.984	0.937	0.941	0.924	0.974		0.991	0.792	0.831		
	At (Tot)	0.965	0.957	0.904	0.968	0.974	0.993	0.844	0.915	0.818	0.848	0.944			
C-4 k=2	Nozzle Vel.	55.5	57.2	59.65	56.6	56.91	62.27	58.92	62.47	52.80	52.14	57.74	54.23		
	Stream Vel.	50.7	49.24	56.19	50.8	52.23	59.22	52.73	59.68						
	SIMS-EGR Diff.			-6.95			-6.99		-6.95						
	At (10)	0.933	0.903	0.913	0.922	0.941	0.921	0.925	0.923		0.945	0.931	0.924		
	At (10)	0.976	0.969	0.964	0.970	0.980	0.966	0.973	0.967		0.980	0.838	0.829		
	At (Tot)	0.945	0.922	0.927	0.938	0.955	0.932	0.938	0.932	0.784	0.939	0.933			
B-5 k=3	Nozzle Vel.	66.8	57.2	68.19	71	56.91	71.33	58.92	74.41	69.45	67.51	69.09	68.68		
	Stream Vel.	67.5	68.47	66.02	69.2	68.17	67.8	66.52	71.55						
	SIMS-EGR Diff.			-2.45			0.37		-5.03						
	At (10)	1.009	1.150	0.933	0.972	1.143	0.913	1.092	0.922		0.997	0.967	0.816		
	At (10)	1.000	1.060	0.970	0.991	1.050	0.964	1.030	0.967		1.001	0.899	0.838		
	At (Tot)	1.010	1.120	0.945	0.988	1.100	0.934	1.070	0.940	0.832	1.093	0.962			
Spatial Averages															
	Nozzle Vel.	54.83	57.20	58.95	56.70	56.91	62.40	58.92	63.40	53.97	54.10	57.52	55.20	2.57	
	Stream Vel.	52.50	55.58	55.31	53.27	56.49	57.97	55.74	60.04						
	SIMS-EGR Diff.			-2.14			-3.29		-6.18						
	Traverse PM10	77.81	66.30	56.20	85.13	103.60	85.50	103.90	78.80		102.61	107.31	92.01		100.65
	Traverse Tot Mass	142.72	129.80	114.60	149.14	206.90	199.70	227.70	188.70		193.09	221.37	201.97		205.48
	PM10 Fraction	54.67	51.079	49.040	57.084	50.072	42.814	45.630	41.759	53.59	48.97	45.77	49.44		
	At (10)	0.972	0.983	0.913	0.952	0.997	0.903	0.964	0.916	0.978	0.980	0.898			
	At (10)	0.988	0.997	0.970	0.983	0.997	0.958	0.984	0.969	0.992	0.990	0.955			
	At (Tot)	0.978	0.980	0.928	0.967	0.993	0.923	0.968	0.930	0.981	0.976	0.927			
	Corrected PM10	78.8	66.3	57.9	86.6	103.9	89.2	105.6	81.3	103.433	108.265	96.325			
	Corrected PM10 diff.			8.56			14.66		24.27	196.949	228.388	210.852	7.090		
	Corrected traverse Tot Mass	148.9	133.4	123.5	154.2	208.4	216.4	235.2	202.9						
	At (10)			8.56			-8.00		32.32				8.260		
	At (Tot)	54.0	50.0	46.9	56.2	49.9	41.3	44.9	40.1		52.964	47.921	44.013		15.070
	Corrected PM10 fraction			3.29			8.62		4.81				4.369		3.100

b No impactor run with.

c Measured values are 20.9 and 22.2 (PM10 and Tot Mass); recycle and sample lines were reversed. Refer to test for source of value given.

The magnitude of error due to anisokinetic sampling in these measurements is also of interest. For the impactors, correction for anisokinetic sampling changed PM_{10} by less than 1% and the total concentration by 2%. For SIM-5 this correction changed the PM_{10} by 1% and total concentration by 4%. For EGR this correction changed the PM_{10} by 4% and total concentration by 4%. Most of the correction in the EGR results was due to an apparent bias in the EGR pitot reading.

The rate of variation of average aspiration coefficient with percent isokinetic is also of interest. In other words, how much error was introduced for every 10% off of isokinetic sampling at this source? A useful quantity to describe this sampling error is $B/(B+1)$ in Equation 3-1 averaged over particle size distribution. Although this factor rigorously involves stream and nozzle velocity it is somewhat insensitive to their changes. In this field test, this factor averaged 0.27 with standard deviation of 0.036 for PM_{10} and 0.57 with standard deviation of 0.058 for total particulate concentration. This means that for every 10% off of isokinetic, 3% error was introduced in PM_{10} measurements and 6% error in total particulate concentration.

Differences in Particle Size Cuts

Differences between flowrates of the cyclones used with EGR and SIM-5 were never more than 3%. According to Equation 3-2 the predicted size cuts for Cyclone I could not have differed by more than 0.2 μm . This difference cannot explain the minimum of 5% difference in PM_{10} concentrations observed with EGR and SIM-5 which persist after correction for anisokinetic sampling.

Since the EGR recycle nozzle combines clean recycle air as a sheath with aerosol entering Cyclone I, the geometry of the aerosol stream is different from the geometry of Cyclone I with a standard nozzle. It appears reasonable that the particle collection characteristics of Cyclone I may be altered by this change in the geometry of the aerosol stream at the cyclone entrance. This mechanism may be the cause of the 5% difference observed between EGR and SIM-5 PM_{10} concentrations. Using the cumulative percent in Figure 6-7 measured with impactors the 5% difference in PM_{10} concentration can be related to a shift in the size cut of the cyclone used with EGR of about 1.5 μm below that with SIM-5. It cannot be certain that a difference in cutpoint caused the observed difference in PM_{10} . This potential mechanism is discussed further in Section VIII for all of the field tests of this project.

Accuracy of SIM-5 and EGR Techniques

Single point impactor measurements each sampling isokinetically were obtained as the best available reference data in this study. The results of the measurements are given in Table 6-2. The differences of impactor results from each of the SIM-5 and EGR results are given in Table 6-5 along with 95% confidence limits. Confidence limits for the average for each technique are also given. No significant differences can be distinguished between EGR and single point impactors or between SIM-5 and single point impactors with 95% confidence for either PM_{10} or total particulate concentration. The impactor measurements could not be performed simultaneously with the SIM-5 and EGR

Table 6-5. Comparison of Particulate Concentrations
Measured by Impactors, SIM-5, and EGR

	<u>No. of Observations</u>	<u>Average^a</u>	<u>95% Confidence Limits^a</u>
<u>PM₁₀</u>			
Impactor	6	103	±22
SIM-5	7	107	±20
EGR	6	92	±26
Difference:			
Impactor - SIM-5	5	-3.8	±25
Impactor - EGR	5	-11	±31
<u>Total Mass</u>			
Impactor	6	193	±49
SIM-5	7	221	±51
EGR	5	196	±72
Difference:			
Impactor - SIM-5	5	-28	±62
Impactor - EGR	5	-2.6	±73

^aAll concentrations are given in mg/dncm.

measurements. It appears that temporal variations obscure the relatively small differences in the techniques. Note that this analysis was performed with SIM-5 and EGR results without the corrections described in preceding sections. These errors, though real, are still small compared to the temporal variations encountered at this source.

Spatial and Temporal Variations

A major objective of this field test was the determination of the difference or bias between SIM-5 type measurements and EGR measurements. The observed temporal variation for this source is also relevant to the total measurement error to be expected from PM_{10} measurements in general. Spatial variation is also directly observable in the impactor measurements and of similar importance in general.

Each PM_{10} value, w_{kl} , measured with the single point impactors can be characterized as

$$w_{kl} = \mu + \alpha + \beta_k + \gamma_l + \epsilon_{kl} \quad (6-3)$$

where μ = the true average PM_{10} concentration (emission rate/average velocity).

α = bias which the impactor technique may possess.

β_k = bias related to the k th sampling point with the restriction that $\sum \beta_k = 0$.

γ_l = portion of the measurement due to time variation. It is ideally a random variable with average of 0 and standard deviation σ_t .

ϵ_{kl} = other deviations not characterized by the other parameters. Commonly referred to as residue; it is ideally a random variable with average of 0 and standard deviation σ .

Note that in reality the differences between points could vary with time rather than remain constant as in the model used. For simplicity, that possibility is not treated directly, but it effects the residues, causing the deviations for each point to be larger.

The SIM-5 and EGR measurements were subject to similar variations to those in Equation 6-3 except these probes traversed the three points measured individually with impactors. There is, however, no contradiction in terminology using the same model for SIM-5 and EGR results with β_k determined from the impactors. To compare the three techniques on the same basis each PM_{10} value was characterized as

$$w_{jkl} = \mu + \alpha_j + \beta_k + \gamma_l + \epsilon_{jkl} \quad (6-4)$$

where j denotes the technique (for impactors $j=1$, for SIM-5 $j=2$, and for EGR $j=3$). In this model each SIM-5 or EGR measurement is the average of w_{2kl} (SIM-5) or w_{3kl} (EGR) over k , respectively. The results given in Table 6-2 were employed to calculate these parameters,

where μ = average of traverse concentration for all techniques denoted by $w_{...}$,

$\alpha_j = w_{j..} - w_{...}$
 = the deviation from $w_{...}$ of the average results from each technique,

$\beta_k = w_{1k.} - w_{...}$
 = the deviation from $w_{...}$ of the average impactor results for each point k,

$\gamma_l = w_{1..l} - w_{...}$ for $l = 3, 5, 7, 9, 10$, and 12 or

$= w'_{1..l} - w_{...}$ for $l = 2, 4, 6, 8, 11, 13, 14$,

where $w_{1..l}$ is the traverse PM_{10} from impactors in each set and

$w'_{..l}$ is the average between SIM-5 and EGR for each set.

Tables 6-6 and 6-7 give the results of these calculations. Note that the preceding sections were concerned with the α 's, differences between techniques. The coefficient of variation (COV) for spatial and temporal variations are relevant to estimating uncertainty to be expected in emission rate measurements at this source as a function of the number of replications performed.

The two columns for spatial variation represent two quantities of interest. The "not weighted" results are a measure of the spatial variation of PM_{10} and total mass concentrations. As can be seen, both concentrations are essentially uniform over the three point traverse. The "velocity weighted" results show the spatial variance of the PM_{10} and total mass emission rate, which reflects the velocity stratification of the three points chosen.

Table 6-6. Components of Observed PM_{10} Concentrations
(Given in % of Average)

Technique	α_j	Spatial Variation, β_k			Time Segment, l	Temporal Variation, γ_l
		Point	Velocity Weighted	Not Weighted		
Impactor	2	E-6	-24	3	2	14
					3	-12
SIM-5	7	C-4	-2	-1	4	0
					5	20
EGR	-9	B-5	26	-2	6	0
					7	24
					8	33
					9	18
					10	-23
					11	-40
					12	-15
					13	-6
		COV(%) =	25	3	14	-9
					COV(%) =	21

COV(%) of SIM-5(7) and EGR(7) Residues = 3.
COV(%) of 18 Point-by-point impactor residues = 8.

Table 6-7. Components of Observed Total Particulate Concentrations
(Given in % of Average)

Technique	α_j	Spatial Variation, β_k			Time Segment, l	Temporal Variation, γ_l
		Point	Velocity Weighted	Not Weighted		
Impactor	-6	E-6	-32	-7	2	24
					3	-19
SIM-5	8	C-4	4	7	4	-1
					5	2
EGR	-2	B-5	28	0	6	-3.6
					7	23
					8	43
					9	16
					10	-30
					11	-40
					12	-27
					13	-1
					14	1
					COV(%) = 30	7
COV(%) = 24						

COV(%) of SIM-5(7) and EGR(7) Residues = 3.
COV(%) of 18 Point-by-point impactor residues = 10.

SECTION VII

EGR/SIM-5 TEST 3

The site chosen for the fourth test, EGR/SIM-5 comparison test 2, was a 221 MW pulverized coal-fired utility boiler. Combustion gases from the boiler were cooled by heat exchange in two Lungstrom air heaters prior to entering the control device. The control device was separated into two distinct sides (1A and 1B), each side being fed by a separate air heater. ID fans at the outlet exhausted the gas stream to the stack from both sides of the control device (see Figure 7-1).

Sampling took place at the inlet to both Units 1A and 1B. In each instance the site chosen was a 9'x16' rectangular duct with 144 square feet of flow area. Eight four-inch ports provided access to the duct interior. Figure 7-2 shows the duct at the inlet to Unit 1A. The geometry of the duct at Unit 1B was the same with the ports on the opposite side to that shown in Figure 7-2.

Static pressure in the duct was -9.0 inches of water and gas stream temperatures ranged from 250 to 290°F. Stream velocities in duct 1A ranged from 37.0 to 63.5 feet per second with an average of approximately 51 feet per second. The range in duct 1B was 44.6 to 61.0 feet per second with an average of 53 feet per second. Figures 7-3 and 7-4 show representative velocity distributions for ducts 1A and 1B, respectively.

Sampling was also done at the outlet on the stack. Eight four-inch ports 230 feet from the base of the stack at a stack diameter of 20 feet served as the site for control device outlet samples (see Figure 7-5). Stream velocities in the sample plane ranged from 46 to 53 feet per second with an average of 50 feet per second. Figure 7-6 shows a representative velocity distribution. Static pressure in the stack was -0.5 inches of water. This test was performed in conjunction with a project of the Electric Power Research Institute (EPRI). The test plan was designed to evaluate the control device as well as the EGR and SIM-5 protocols.

TEST PROCEDURES

Subtest A: Simultaneous 12 Point EGR and SIM-5 Traverses at the Inlet

The test plan for the concurrent EGR/SIM-5 test series at the inlet was similar to that of Test 3. The primary difference of emphasis was that full duct PM₁₀ emissions measurements were performed rather than a three-point sample. The test plan consisted of two subtests. Subtest A called for simultaneous 12 point EGR and SIM-5 traverses using SORI Five Series Cyclone sets.

Each twelve-point traverse involved sampling at three points in four of the eight ports. The sampling points, designated 1, 2, and 3 were 90, 54, and 18 inches into the duct, respectively. The eight ports available for sampling were grouped into two sets of four, ACEG and BDFH.

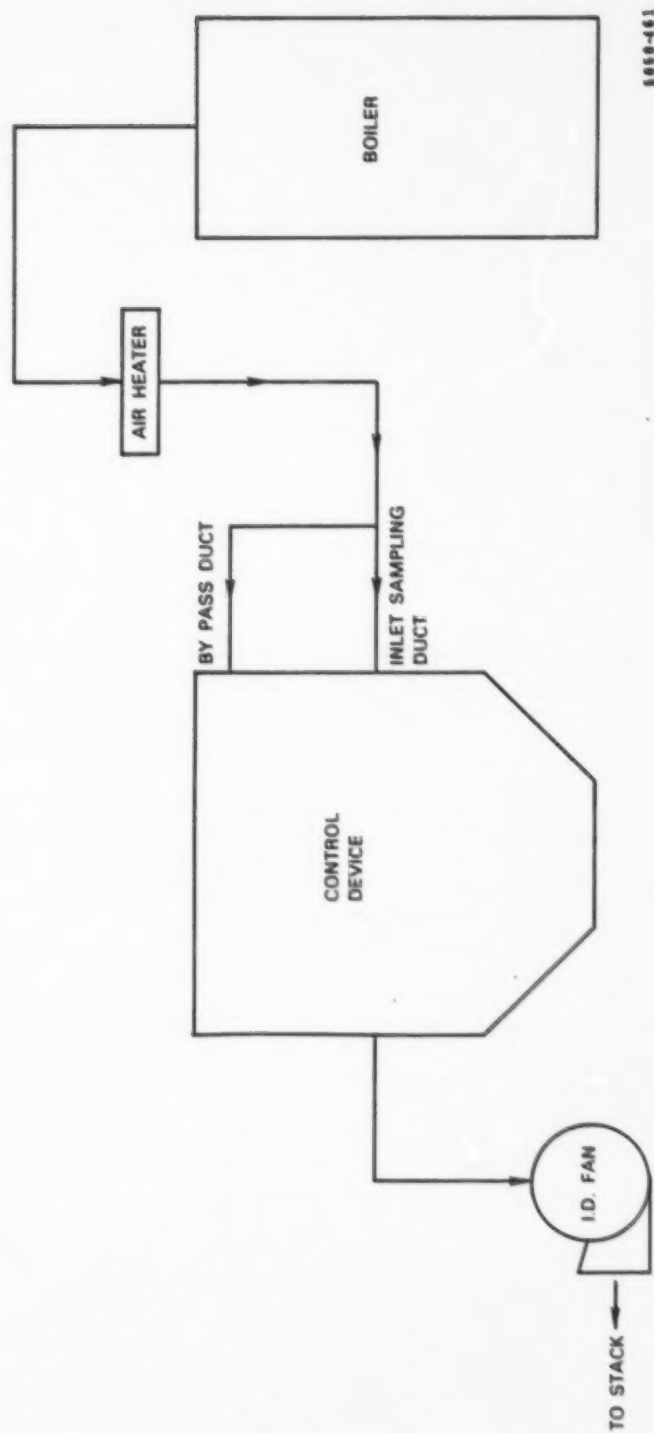


Figure 7-1. Test site for EGR/SIM-5 Test 3.

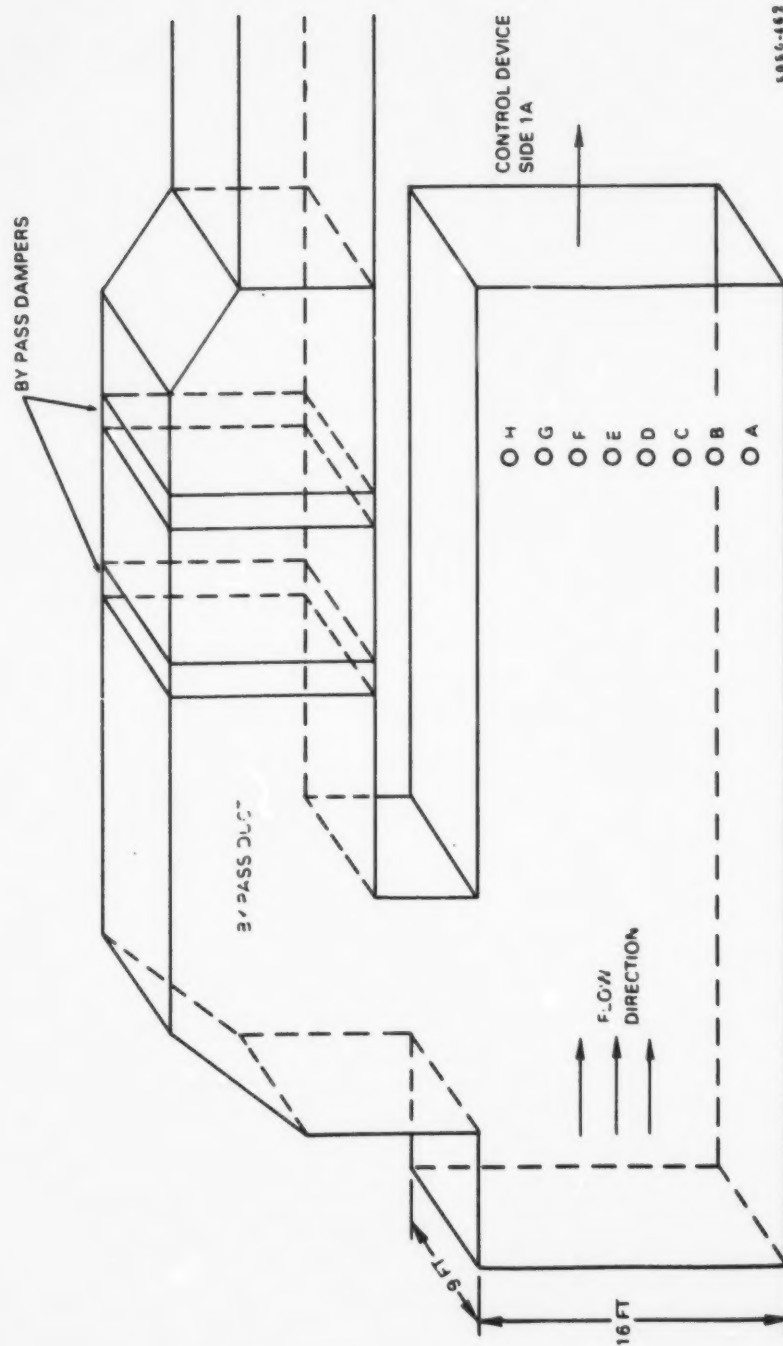


Figure 7-2. Inlet sampling site for control device side 1A.

	A	B	C	D	E	F	G	H	Top
1	54.59	63.64	67.71	53.39	45.30	60.94	52.96	37.32	
2	58.64	59.65	52.38	52.27	59.21	62.70	47.14	44.16	
3	47.82	60.48	59.53	47.66	47.37	54.89	55.70	47.21	
Bottom									

Figure 7-4. Inlet B Velocity Distribution, Feet Per Second

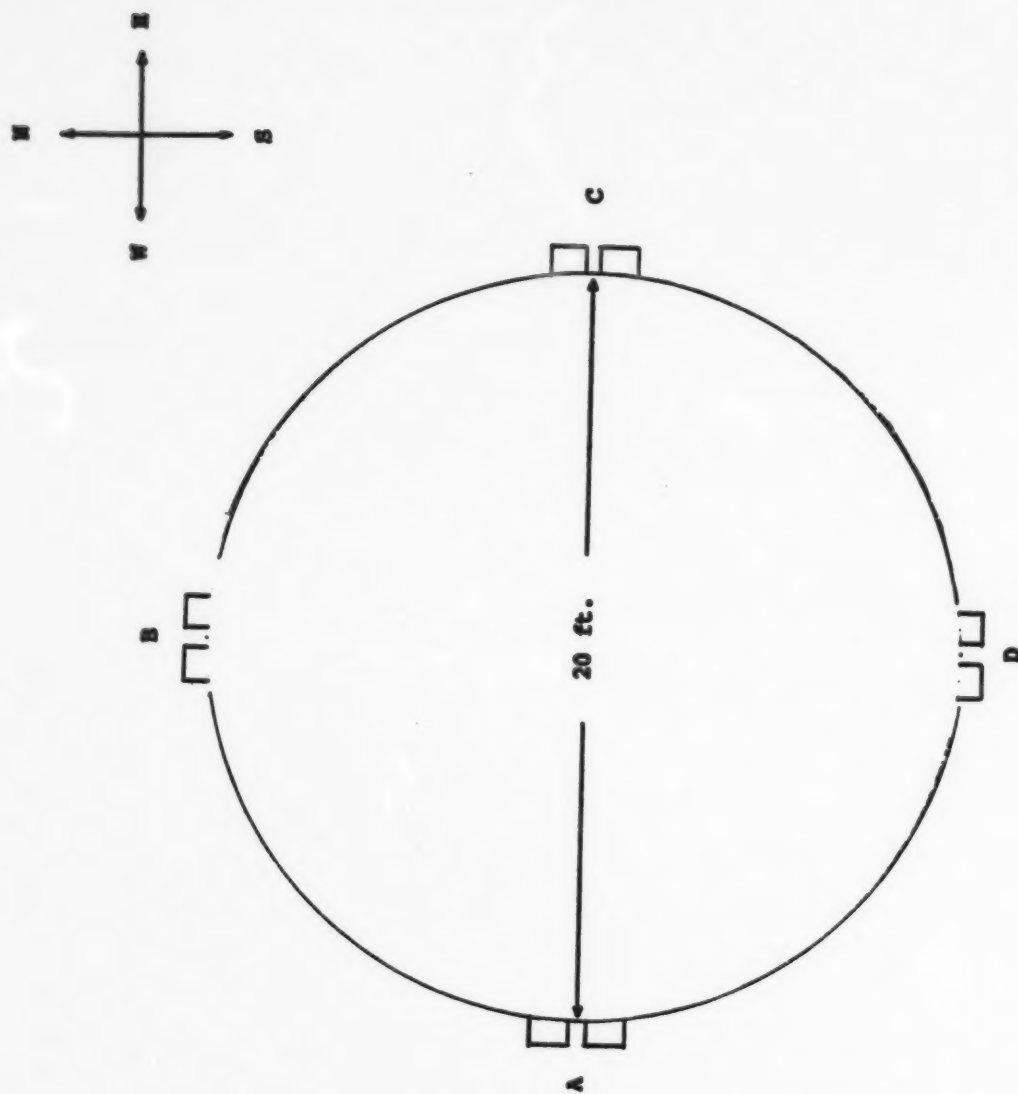


Figure 7-5. Stack sampling site.

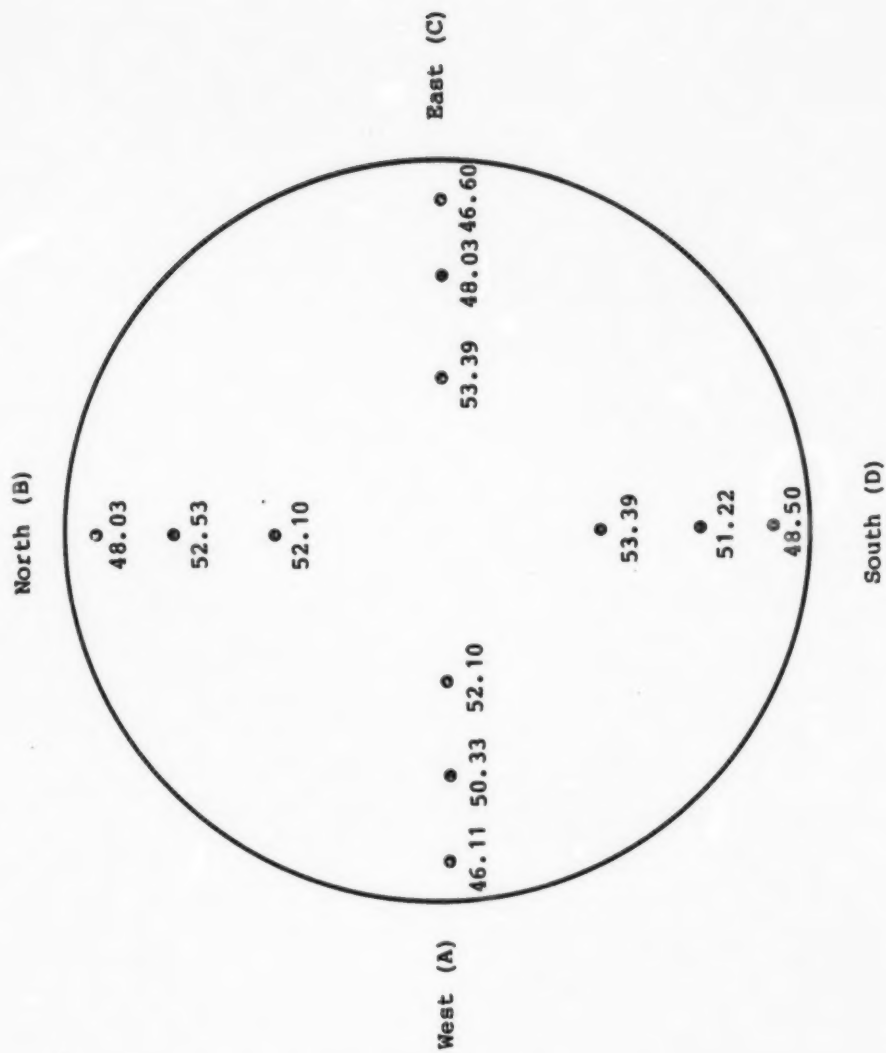


Figure 7-6. Outlet Velocity Distribution, Feet Per Second.

SIM-5 sampling with the cyclones followed the procedure defined by Table 7-1. The actual flowrate was determined by the expression for Q (Equation 3-3) to give a 10 μm size cut for Cyclone I. The viscosity necessary for this calculation was determined from

$$\mu = C_1 + C_2 T + C_3 T^2 + C_4 f_{\text{H}_2\text{O}} + C_5 f_{\text{O}_2} \quad (7-1)$$

where $C_1 = 51.050$
 $C_2 = 0.20678$
 $C_3 = 3.2355 \times 10^{-5}$
 $C_4 = -74.143,$
 $C_5 = 53.147,$

T is the flue gas temperature in $^{\circ}\text{R}$, $f_{\text{H}_2\text{O}}$ is mole or volume fraction of water and f_{O_2} is the same for oxygen (Williamson, et al., 1983). The water composition was assumed from previous test data at the same plant on the first run and from the preceding run on succeeding runs. The O_2 was determined by Fyrite on the first run and by Orsat for succeeding runs. After Q was determined the product $\mu/\bar{Q}$ was calculated for use in the SIM-5 nomograph (Figure 6-3) to determine upper and lower limits for stream velocity, $v_{\ell\ell}$ and $v_{u\ell}$. These limits change with the nozzle diameter. Upper and lower velocity limits were calculated for three prospective nozzles. For each, the nozzle velocity, u , was calculated and $v_{\ell\ell}$ and $v_{u\ell}$ read from the nomograph. This was accomplished by overlaying the $R=v/u$ curve in that figure so that its center ($R=1$) matched the nomograph at $R=1$ and the abscissa at $v=u$. Then $v_{\ell\ell}$ and $v_{u\ell}$ were read as the velocities at which the $R=v/u$ curve intersected the appropriate curve for $\mu/\bar{Q}$. The nozzle was chosen which provided $v_{\ell\ell}$ and $v_{u\ell}$ values bracketing the velocities of the points to be sampled. Since in practice these were not precisely known prior to a run because of temporal variations, the velocity limits were converted to corresponding ΔP limits for the pitot used on the SIM-5 probe. Then the operator knew during the run if the current stream velocity was above or below the limits for the nozzle being used. This did not occur in any of the runs in this test.

After identifying the nozzle to use in each run and its corresponding ΔP limits, the pressure drop, ΔH , across the sample flow orifice was calculated. This value was necessary to adjust the sample flow to the appropriate flowrate, Q . The remaining parameter needed for each run was dwell time at each point. The dwell time for the first sample point was calculated prior to starting the run using the ratio $\sqrt{\Delta P_1}/\sqrt{\Delta P}$ from a previous run or velocity traverse. Then each succeeding dwell time, t_n , of a new run was calculated during the run from the expression given in Table 7-1 using t_1 and ΔP_1 for the first sample point of the new run.

Four sets of simultaneous EGR and SIM-5 runs were performed at the inlet to Unit 1A. Two simultaneous traverses were performed in ports ACEG and two in ports BDFH. Two replicates were performed in the duct at the inlet to Unit 1B. Both traverses used ports ACEG.

Table 7-1. SIM-5 Cyclones

$$Q_n = 7.863 \times 10^7 \mu^2 .228 = 7.863 \times 10^7 (225 \times 10^{-6})^2 .228 = \underline{0.5865}$$

$$\mu \sqrt{Q_n} = \frac{(225 \times 10^{-6})}{10^{-6}} \sqrt{(0.5865) \times 28.32} = \underline{917}$$

$$V_{\text{nozzle}} = 3.056 Q_n / d^2 = 3.056 (0.5865) / d^2 = \underline{1.792 / d^2}$$

Nozzle I.D.	11	10	9
Diameter =	<u>0.154</u>	<u>0.173</u>	<u>0.194</u>
$V_{\text{nozzle}} =$	<u>75.58</u>	<u>57.89</u>	<u>47.62</u>
$V_{ll} =$	<u>55.7</u>	<u>42.0</u>	<u>30.8</u>
$V_{ul} =$	<u>94.8</u>	<u>74.5</u>	<u>60.0</u>

$$\Delta P = 1.368 \times 10^{-4} \frac{P_{\text{stk}}}{T_{\text{stk}}} M \frac{1}{w C_p} v^2 = 1.368 \frac{(23.8)(29.56)}{(740)(0.732)^2} v^2 = \underline{2.49 \times 10^{-4}} v^2$$

$$M_w = M_d(1-f_{H_2O}) + M_{H_2O} f_{H_2O} = (30.32)(1-0.062) + 18(0.062) = \underline{27.56}$$

$$\Delta P_{ll} = \underline{0.775} \quad \underline{0.441} \quad \underline{0.237}$$

$$\Delta P_{ul} = \underline{2.250} \quad \underline{1.387} \quad \underline{0.899}$$

ΔP 's From Last Traverse

Point #	Port A	Port B	Port C	Port D	Port E	Port F	Port G	Port H
1	0.690		0.916		0.502		0.690	
2	0.904		0.778		0.878		0.502	
3	0.690		0.841		0.627		0.816	

Note: If ΔP of a point is found to be out of range for the current nozzle, skip it and come back to it after changing to the appropriate nozzle.

$$\Delta H = Q_n^2 \frac{T_{dqm}}{T_{\text{stk}}^2} \frac{P_{\text{stk}}^2}{P_o} (1-f_{H_2O})^2 M_d K_{\text{cal}}$$

$$= (0.5865)^2 \frac{(510)}{(740)^2} \frac{[(24.5) + \frac{(-9)}{13.6}]^2}{[(24.5) + \frac{(4.5)}{13.6}]} (1-0.062)^2 (30.32) K_{\text{cal}} = \underline{0.1956} K_{\text{cal}} = \underline{4.0}$$

DWELL TIMES

$$t_1 = \frac{\sqrt{\Delta P_1}}{(\sqrt{\Delta P})} \frac{\text{Total run time}}{\text{No. points}} = \frac{(0.557)}{(0.826)} (5) = \underline{3.33}; t_n = t_1 \sqrt{\frac{\Delta P_n}{\Delta P_1}} = (3.33) \sqrt{\frac{\Delta P_n}{()}}$$

Point #	Port A	Port B	Port C	Port D	Port E	Port F	Port G	Port H
1	3.0		5.0		3.5		4.0	
2	4.5		4.0		4.5		3.5	
3	4.0		3.0		4.0		4.5	

Subtest B: Four Simultaneous Three-Point Impactor Traverses at the Inlet

Subtest B determined reference size distributions using University of Washington Mark V impactors. A Flow Sensor precutter was used to turn the flow 90 degrees. The precutter size cut was determined from laboratory calibration work in EPA Contract 68-02-3118. The jet plates chosen for this subtest are designated 1, 2, 3, 4, 5, 7, and 11 by the manufacturer (Pollution Control Systems). The cascade impactors were operated over the same 12-point traverse used for Subtest A. The traverse was subdivided by port into four simultaneous impactors, each traversing three points; each subtraverse was sampled using SIM-5 protocol, the flowrate fixed so that the nozzle velocity equaled the mean measured velocity for the three-point subtraverse. The four impactors in a set were not absolutely simultaneous, but run in series, 15 minutes for each, over a 1 1/2 hour period.

Five sets of Subtest B were completed. Four were performed in duct 1A, two in ports ACEG, two in ports BDFH. One set was performed in ports ACEG of duct 1B.

Subtest C: Method 17 at the Inlet

An independent subcontractor performed Method 17 sampling at the inlet. A total of six Method 17 mass train samples were obtained at the inlet 1B while Subtests A and B were performed on side 1A. The first three samples traversed the duct in all eight ports, five sampling points per point, as shown in Figure 7-7. The remaining three mass train runs also traversed all eight ports but the number of sampling points per port was reduced from five to three. The three points sampled were those used for the EGR SIM-5 traverses.

Five mass train samples were run at the inlet to Unit 1A. All five runs used the 24-point traverse described above.

Subtest D: Simultaneous Impactor Traverses at the Outlet

Six sets of impactors were run at the outlet sampling site. The impactor configuration used was the same as at the inlet with the exception of the last stage. All outlet impactors used jet plate 10 instead of 11. For tests 1 through 4, two impactors traversed the stack simultaneously, each sampling at the eight points shown in Figure 7-8. The impactor nozzle velocity was set at the average of the velocities at the eight sampling points and kept constant throughout the traverse. For tests 5 and 6, four impactors sampled in the stack simultaneously, one in each port. Each impactor traversed the two sampling points within the assigned port. The nozzle velocity was set at the average of the stream velocities at the two sampling points and held constant.

Subtest E: Method 17 at the Outlet

Eight Method 17 mass train samples were taken at the outlet sampling site. Each run consisted of a three point traverse of each port as shown in Figure 7-9. The nozzle velocity at each point was adjusted to maintain isokinetic sampling as per Method 17 protocol.

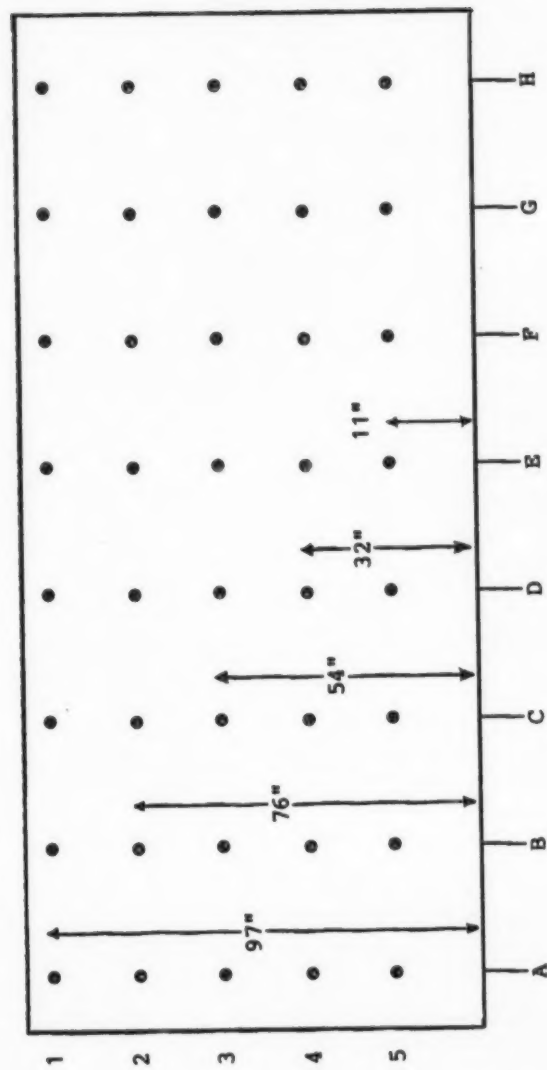


Figure 7-7. 40 Point Inlet Mass Train Traverse

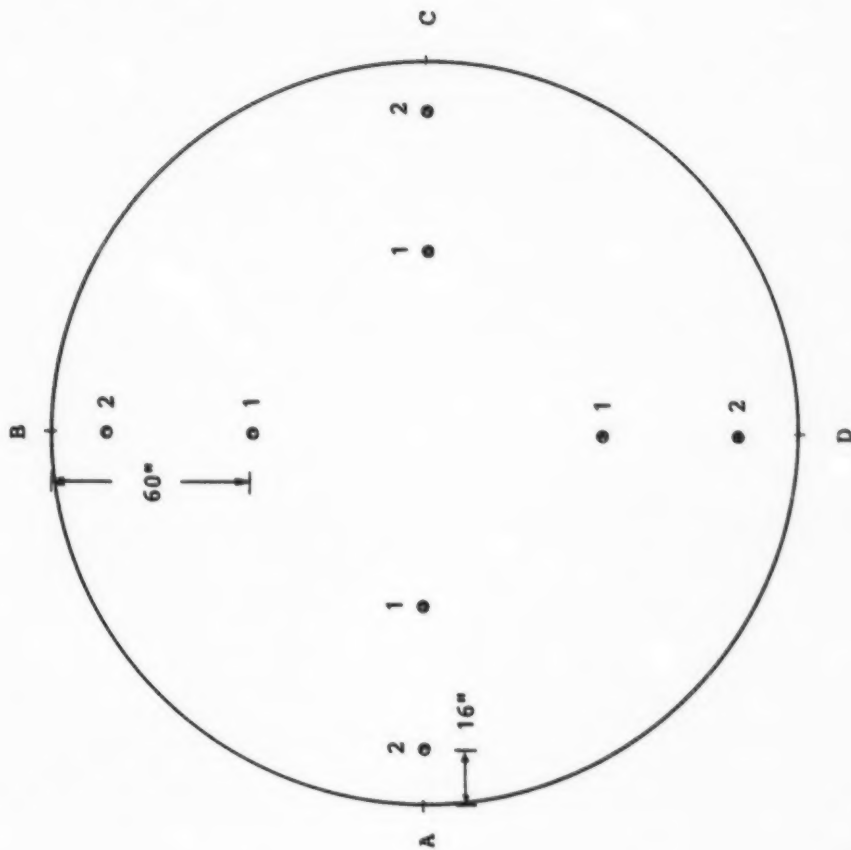


Figure 7-8. Stack Traverse Points.

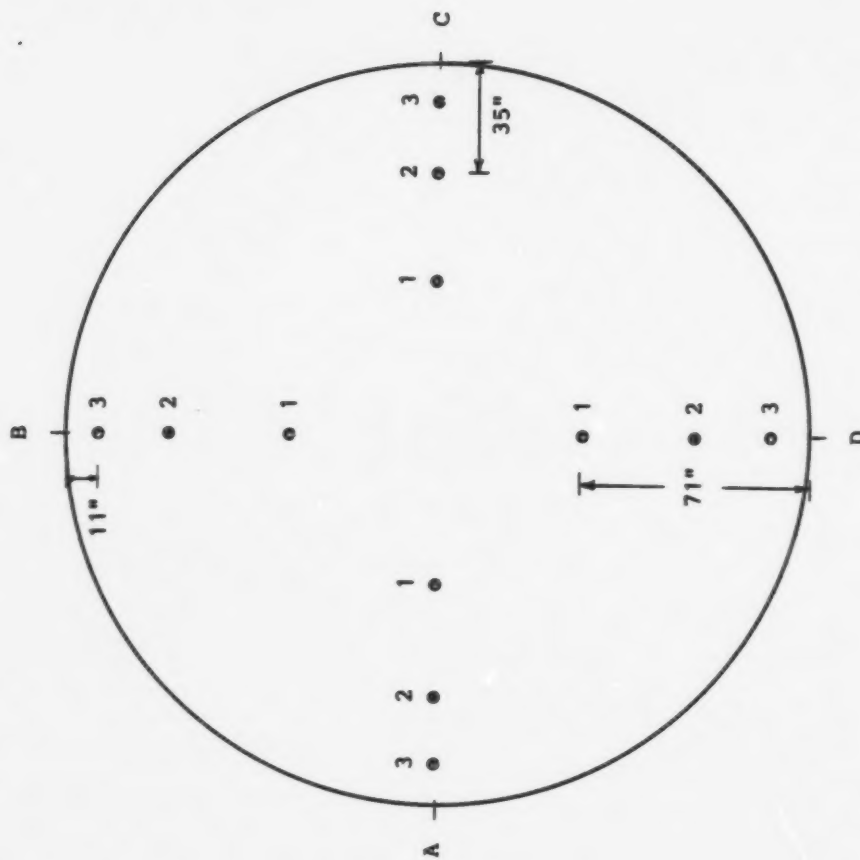


Figure 7-9. Outlet Method 17 Traverse Points.

PRACTICAL PROBLEMS

The heavy particulate loading at the control device inlet posed a problem as it dictated impactor run times of approximately six minutes. This gave the operators very little time to determine the actual run time required by SIM-5 protocol, and in some cases the impactors over-sampled at a traverse point because of this.

The high negative pressure at the inlet also added to the difficulty of the test. The backup filter for the first SIM-5 cyclone run was ruptured when the duct vacuum sucked flow backwards through the probe. To prevent any further problems of this sort, the sample line was clamped off whenever the pump was off.

Attempts to take total particulate samples with fiberglass thimbles at the inlet between impactor and cyclone runs were discontinued after two unsuccessful attempts. The mass train thimble became separated from the sample nozzle during the first run. To prevent this from happening a second time, the collar attaching the thimble to the nozzle was tightened more securely. However, when the pump vacuum exceeded 7 in. Hg during the traverse, the thimble ruptured along the collar.

Other problems encountered at the inlet were probes rotating out of flow, inflow of ambient air through the ports disrupting temperature readings, power outages during test runs, and time restrictions. The latter problem limited test runs at inlet 1B to one impactor set and two cyclone sets.

The primary problem at the outlet was caused by the long run times required to obtain a significant impactor loading. A complete, eight point traverse of the stack by one impactor took approximately eight hours. High wind warnings suspended outlet sampling for part of November 2, forcing the last traverse point for both impactor runs to be neglected.

Long run times also affected the single port, two point impactor runs performed during the second week of the test. To maintain reasonable working hours, the dwell time at the second traverse point was cut short on all runs.

No pitot readings were recorded during the traverse of port B for Test 5 at the outlet because of leaks in the magnehelic. The velocity was assumed to be the average of previous pitot readings in this port and the orifice ΔH was set accordingly.

RESULTS

Table 7-2 gives the time of the various subtests and their locations.

Subtest A: Simultaneous EGR/SIM-5 12 Point Traverses at the Inlet

The major parameters and results of Subtests A and B are given in Table 7-3. Impactor sets are grouped with the SIM-5/EGR sets which were performed nearest in time. The nozzle and stream velocities and percent isokinetic are

Table 7-2. Test 4 Chronology

Date	Inlet 1A	Inlet 1B	Stack
10/29/84	UW Pretest (UW 64)		UW Pretest (UW 65)
10/30/84	SIM-5/EGR 1 @ 10:00-11:30 Imp Set 1 (UW 68, 69, 70, 71) @ 13:50-14:50 SIM-5/EGR 2 @ 16:50-18:10		Imp Set 1 (UW 66, 67)
10/31/84	Imp Set 2 (UW 73, 74, 75, 76) @ 10:50-11:50 SIM-5/EGR- @ 13:30-14:50 Imp Set 3 (UW 78, 80, 81, 82) @ 18:20-19:20	MT-1B @ 15:50-17:20	Imp Set 2 (UW 77, 79) MT-1 @ 15:54-17:58 MT-2 @ 09:40-12:29
11/1/84	SIM-5/EGR 4 @ 09:50-11:10 Imp Set 4 (UW 85, 86, 87, 88) @ 13:15-14:15	MT-2B @ 09:50-12:15 MT-3B @ 13:15-15:45 MT-4B @ 18:00-19:05	Imp Set 3 (UW 83, 84) MT-3 @ 13:17-15:46
11/2/84	MT-1A @ 09:30-11:20 MT-2A @ 13:00-14:00 MT-3A @ 15:40-17:40	SIM-5/EGR5 @ 10:10-11:30 Imp Set 5 (UW 92, 93, 94, 95) @ 14:00-15:50 SIM-5/EGR 6 @ 16:10-17:30	Imp Set 4 (UW 89, 91) Imp Blank 2 (UW 90) MT-5 @ 14:50-17:24 MT-6 @ 14:43-17:15
11/5/84	MT-4A @ 10:30-12:15 MT-5A @ 13:00-14:50		Imp Set 5 (UW 96, 97, 98, 99)
11/6/84		MT-5B @ 10:10-11:55 MT-6B @ 12:55-14:40	Imp Set 6 (UW 100, 101, 102, 103) MT-7 @ 11:00-13:30 MT-8 @ 14:45-17:12

MT 1B - SIM-5/EGR 3
 MT 2B - SIM-5/EGR 4
 MT 1A - SIM-5/EGR 5
 MT 1B - Imp. Set 3
 MT 3B - Imp. Set 4

Table 7-3. Results of Subtest A: Simultaneous EGR and SIM-5 Cyclones with Reference Impactors (Page 2 of 3).

Test 4											
Test 3											
Test 2											
Test 1											
Test 0											
Test -1											
Test -2											
Test -3											
Test -4											
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given for each sampling point for all runs. Since there was an impactor run for each port (3 points/port), PM_{10} and total mass concentrations, and the corresponding velocity weighted concentrations, and PM_{10} fraction are given for each port for the impactor sets.

At the bottom of Table 7-3 spatial averages for each subtest are given. Values for nozzle velocity and stream velocity are simple averages for the traverse. Under columns for impactor data, a value for " PM_{10} " is given and a value for "Traverse PM_{10} ". The former is a simple average of the concentration obtained directly from the impactor runs while the latter is the corresponding velocity weighted average. Similar values are given for total mass concentrations. The average PM_{10} fraction is the ratio of velocity weighted average PM_{10} and total concentration. Of course the concentrations obtained directly from SIM-5 and EGR runs are listed at "Traverse" concentrations (i.e., velocity weighted). The difference between SIM-5 and EGR concentrations and PM_{10} fractions are also listed for each test. Note that the SIM-5 and EGR runs were paired, simultaneous but not colocated traverses. At the right side of Table 7-3 (3rd page), averages and standard deviations are given. These averages are also listed later with corresponding 95% confidence limits in Summary of Results (Tables 7-7 through 7-9).

SIM 5-EGR Differences--

The differences between the SIM-5 and EGR for these tests, given under spatial averages in Table 7-3, are of primary interest. For PM_{10} the SIM-5 results averaged 87 mg/dncm lower than the EGR results with 95% confidence limits of ± 74 . The percent difference was $-11\pm 9\%$. For total mass concentration the average of the difference was relatively small, -62 mg/dncm with the SIM-5 concentration lower, but the variation of these differences was quite large, 95% confidence limits of 722. The percent difference was $-1\pm 21\%$. For PM_{10} fraction the SIM-5 results averaged lower than the EGR results, $-2.1\pm 5\%$. These data are analyzed further below.

Size Distributions from Subtest B

Figure 7-10 gives average cumulative loading versus aerodynamic particle size for all inlet impactor runs. Ninety percent confidence limits are given, being relatively small, $\pm 4\%$ for sizes $> 1 \mu m$ increasing to $\pm 18\%$ at $0.4 \mu m$. These confidence limits are for the simple average concentrations of the twenty impactor runs. Individual runs varied from 3713 to 4658 mg/dncm for total mass concentration and from 538 to 695 mg/dncm for PM_{10} (from Table 7-3). Figure 7-11 presents the average differential size distribution for all impactor runs. The larger 90% confidence limits, relative to those in Figure 7-10, reflect variations between size bands that are irrelevant to cumulative loading. Figure 7-12 presents the average cumulative percent for all runs. The MMD was $35 \mu m$. Note that this value involves extrapolation of cumulative loading from about $15 \mu m$. Size distributions for individual runs are presented as tables in Appendix C. The quantities most relevant to this study obtainable from the impactor runs, PM_{10} , total mass concentration, and the PM_{10} fraction for each run are given in Table 7-3.

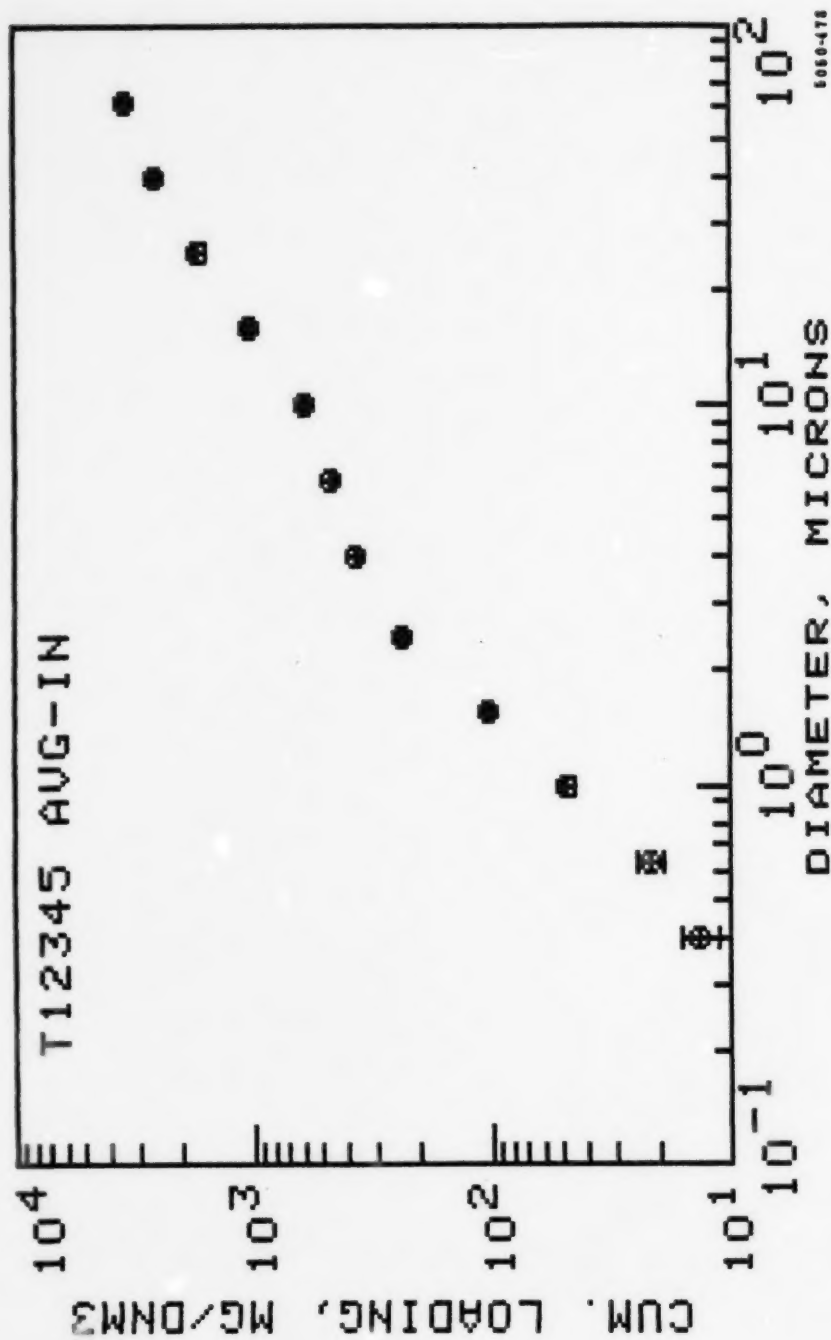


Figure 7-10. Average cumulative loading versus aerodynamic particle size for all inlet impactor runs (EGR/SIM-5 comparison Test 2).

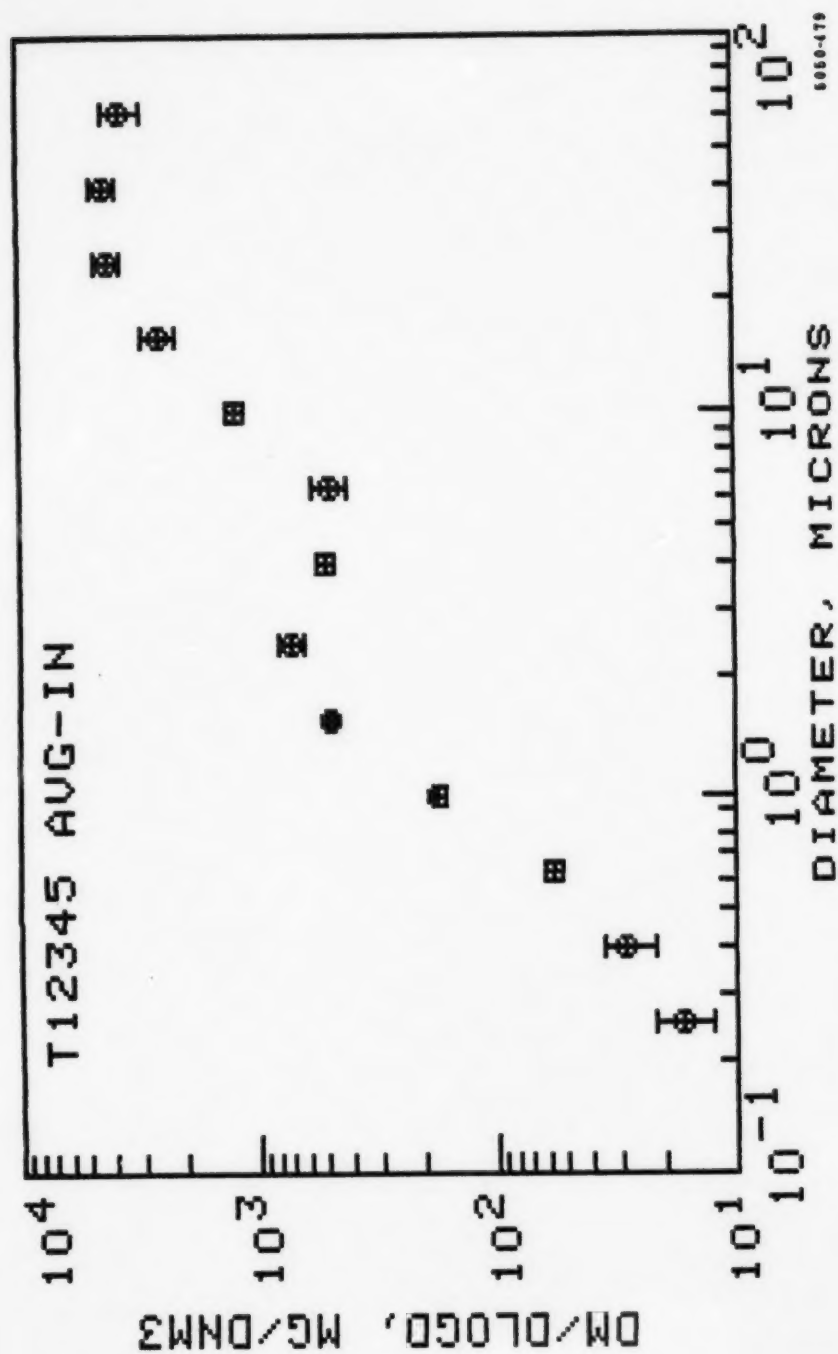


Figure 7-11. Average differential loading versus aerodynamic particle size for all inlet impactor runs (EGR/SIM-5 comparison Test 2).

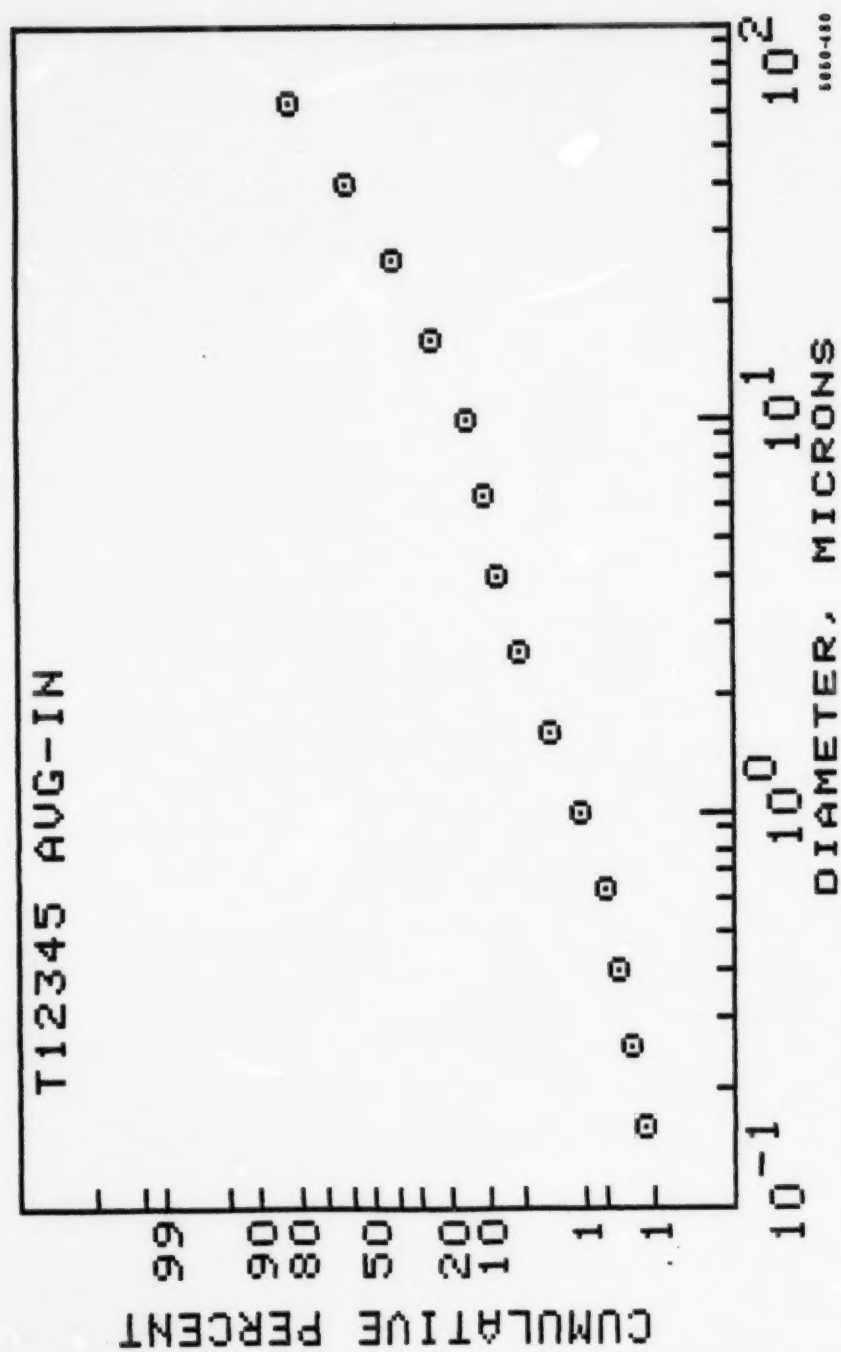


Figure 7-12. Average cumulative percent versus aerodynamic particle size for all inlet impactor runs (EGR/SIM-5 comparison Test 2).

Subtest C: Method 17 at the Inlet

Table 7-4 contains a summary of Method 17 tests at the inlet sampling locations. The data as shown in Table 7-4 yield duct average concentrations of 2658 ± 815 mg/dncm for duct A and 3427 ± 1292 mg/dncm for duct B, with 95% confidence limits shown. Below, these data are compared to total mass concentration measured by impactors and SIM-5 and EGR cyclones.

Subtest D: Simultaneous Impactor Traverses at the Outlet

Table 7-5 summarizes the results of Subtest D. For each traverse point, nozzle and stream velocities, percent isokinetic, and dwell times are given. For the first four tests, PM_{10} and total particulate concentrations (in mg/dncm) obtained directly from impactor runs are given as "Traverse PM_{10} " and "Traverse Tot Mass" because each run traversed the entire duct. In the last two tests PM_{10} and total particulate concentrations obtained directly from impactor runs are given as " PM_{10} " and "Tot Mass". These runs did not traverse the entire duct, only 2 points per run. "Traverse PM_{10} " and "Traverse Tot Mass" values for the last two tests were calculated as a velocity weighted average of the four runs of each test. PM_{10} fraction was obtained from the ratio of "Traverse PM_{10} " to "Traverse Tot Mass". Averages of the traverses and standard deviations are given at the right of this table.

Figure 7-13 gives average cumulative loading versus aerodynamic particle size for all outlet impactor runs. Ninety percent confidence limits are given, being relatively small, $\pm 5\%$, for sizes $> 7 \mu m$ increasing to $\pm 32\%$ at $0.4 \mu m$. The confidence limits are for the simple average of the concentrations of the 16 impactor runs. Of course individual runs varied more, from 12.5 to 17.7 mg/dncm for total particulate concentration and from 2.4 to 3.7 mg/dncm for PM_{10} concentration (from Table 7-5). Figure 7-14 presents the average differential size distribution for all impactor runs. The larger confidence intervals, relative to those in Figure 7-13, reflect variations between size bands that are irrelevant to cumulative loading. As with the inlet aerosol there appears to be two modes with the larger size particles being more prominent in mass concentration. The presence of two modes is less distinct for the outlet aerosol than for the inlet aerosol. Figure 7-15 presents the average cumulative percent for all runs. The MMD was about $25 \mu m$, slightly lower than for the inlet but determination of these MMD's involves extrapolation from about $12 \mu m$ so the difference from inlet to outlet is not considered significant.

Subtest E: Method 17 at the Control Device Outlet

The results of the Method 17 tests in the stack are shown in Table 7-6. The average concentration, including all data with 95% confidence limits is 15.62 ± 3.6 mg/dncm. The data are compared to total particulate concentration values from the impactor runs below (in "Analysis of Results").

SUMMARY OF RESULTS

The major results of this field test are summarized in Tables 7-7 through 7-10 (7-7 through 7-9 for inlet data). Averages and 95% confidence limits of

Table 7-4. Method 17 Total Particulate Test Results

<u>Date</u>	<u>Run</u>	<u>Concentration (mg/dncm)</u>	<u>% Isokinetic</u>
10/31/84	1B	3745	91
	2B	3248	104.6
	3B	3630	102.2
11/1/84	4B	1612	109.6
11/2/84	1A	3174	99.4
	2A	2190	97.2
	3A	1734	104.0
11/5/84	4A	3065	100.9
	5A	3125	101.9
11/6/84	5B	2933	96.1
	6B	5393	

Average A 2658 $\pm$ 815 (95% Confidence, all runs)
 2889 $\pm$ 744 (excluding Run 3A)

Average B 3427 $\pm$ 1292 (95% Confidence, all runs)
 3389 $\pm$ 590 (excluding runs 4B and 6B)

Table 7-5. Results of Subtest D: Simultaneous Impactor Traverses at the Outlet.
(Velocities in feet/sec and concentrations in mg/DNCM).

	Test 1			Test 2			Test 3			Test 4			Test 5			Test 6			Average	Std. Deviation																				
	Imp 1	Imp 2		Imp 3	Imp 4		Imp 5	Imp 6		Imp 7	Imp 8		Imp 9	Imp 10	Imp 11	Imp 12	Imp 13	Imp 14			Imp 15	Imp 16																		
A-1	Vn	46.52	47.31	45.72	45.8		56.06	57.8		53.16	55.29		46.76				49.22																							
	Vs	55.71	54	54.12	53.82		53.82	53.8		54.21	51.21		51.58				53.19																							
	X Iso	83.50	87.61	84.48	84.63		104.16	107.43		98.06	107.97		90.66				92.54																							
	Td	63	61	61	61		61	61		61	61		307				246																							
A-2	Vn	46.52	47.31	45.72	45.8		56.06	57.8		53.16	55.29		46.76				49.22																							
	Vs	50.31	51.74	52.65	51.14		51.24	51.26		52.23	51.17		50.91				52.41																							
	X Iso	92.47	91.44	86.84	89.56		109.41	112.76		101.78	108.05		91.85				93.91																							
	Td	58	58	58	61		58	58		58	60		169				187																							
B-1	Vn	46.52	47.31	45.72	45.8		56.06	57.8		53.16	55.29					51.5					47.99																			
	Vs	54.98	54.84	56.26	56.47		54.78	54.73		53.5	53.06					52.0 a					52.16																			
	X Iso	84.61	86.27	81.27	81.11		102.34	105.81		99.36	104.20					99.04					92.01																			
	Td	61	64	63	64		61	60		60	60					213					246																			
B-2	Vn	46.52	47.31	45.72	45.8		56.06	57.8		53.16	55.29					51.5					47.99																			
	Vs	52.70	51.45	52.00	52.47		51.90	51.78		53.09	50.88					52.0 a					51.19																			
	X Iso	88.27	91.95	87.92	87.29		108.02	111.63		100.13	108.67					99.04					93.75																			
	Td	59	58	58	60		58	58		59	60					184					177																			
C-1	Vn	46.52	47.31	45.72	45.8		56.06	57.8		53.16	55.29					49.5					52.66																			
	Vs	55.72	54	55.6	54.53		55.62	56.65		54.67	52.24					49.82					55.22																			
	X Iso	83.49	87.61	82.23	83.99		100.79	102.03		97.24	105.84					99.36					95.36																			
	Td	64	65	64	67		62	64		61	44					382					248																			
C-2	Vn	46.52	47.31	45.72	45.8		56.06	57.8		53.16	55.29					49.5					52.66																			
	Vs	52.27	51.45	51.33	52.11		53.54	53.58		53.68						49.24					55.22																			
	X Iso	89.00	91.95	89.07	87.89		104.71	107.88		99.03						100.53					51.29																			
	Td	59	68	58	60		60	60		60	60					197					102.67																			
D-1	Vn	46.52	47.31	45.72	45.8		56.06	57.8		53.16	55.29										50.4																			
	Vs	56.39	53.9	55.41	54.97		53.68	53.59		54.18	54.67										55.39																			
	X Iso	82.50	87.77	82.51	83.32		104.43	107.86		98.12	101.13										90.99																			
	Td	63	60	63	62		60	61		60	60										270																			
D-2	Vn	46.52	47.31	45.72	45.8		56.06	57.8		55.29											50.4																			
	Vs	53.12	51.04	53.58	54		51.91	51.43		49.01											52.70																			
	X Iso	87.58	92.69	85.33	84.81		107.99	112.39		112.81											95.64																			
	Td	59	59	60	62		58	58		60											173																			
PM10																																								
Tot Mass																																								
Trace PM10																					3.74	2.64	2.63	2.78		2.8	2.67		2.62	3.42										2.89
Trace Tot Ma																					14.2	14.8	16.3	15.0		13.0	12.5		15.1	16.1										14.5
PM10 Fraction																					26.3	17.6	16.1	18.5		21.5	21.4		17.4	21.2										19.5
																																								2.0

a: Pitot values not recorded due to magnetic leaks.
This velocity assumed.

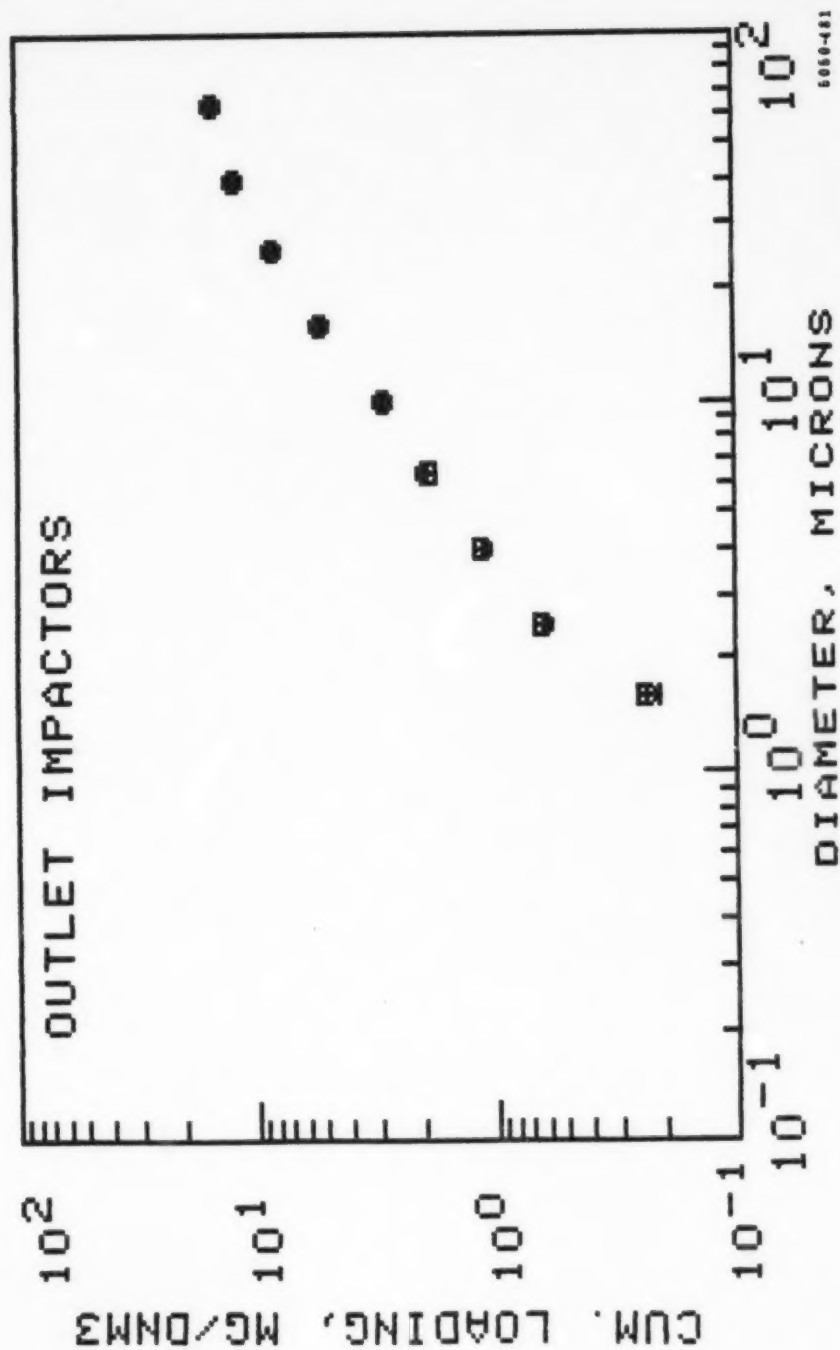


Figure 7-13. Average cumulative loading versus aerodynamic particle size for all outlet impactor runs (EGR/SIM-5 Comparison Test 2).

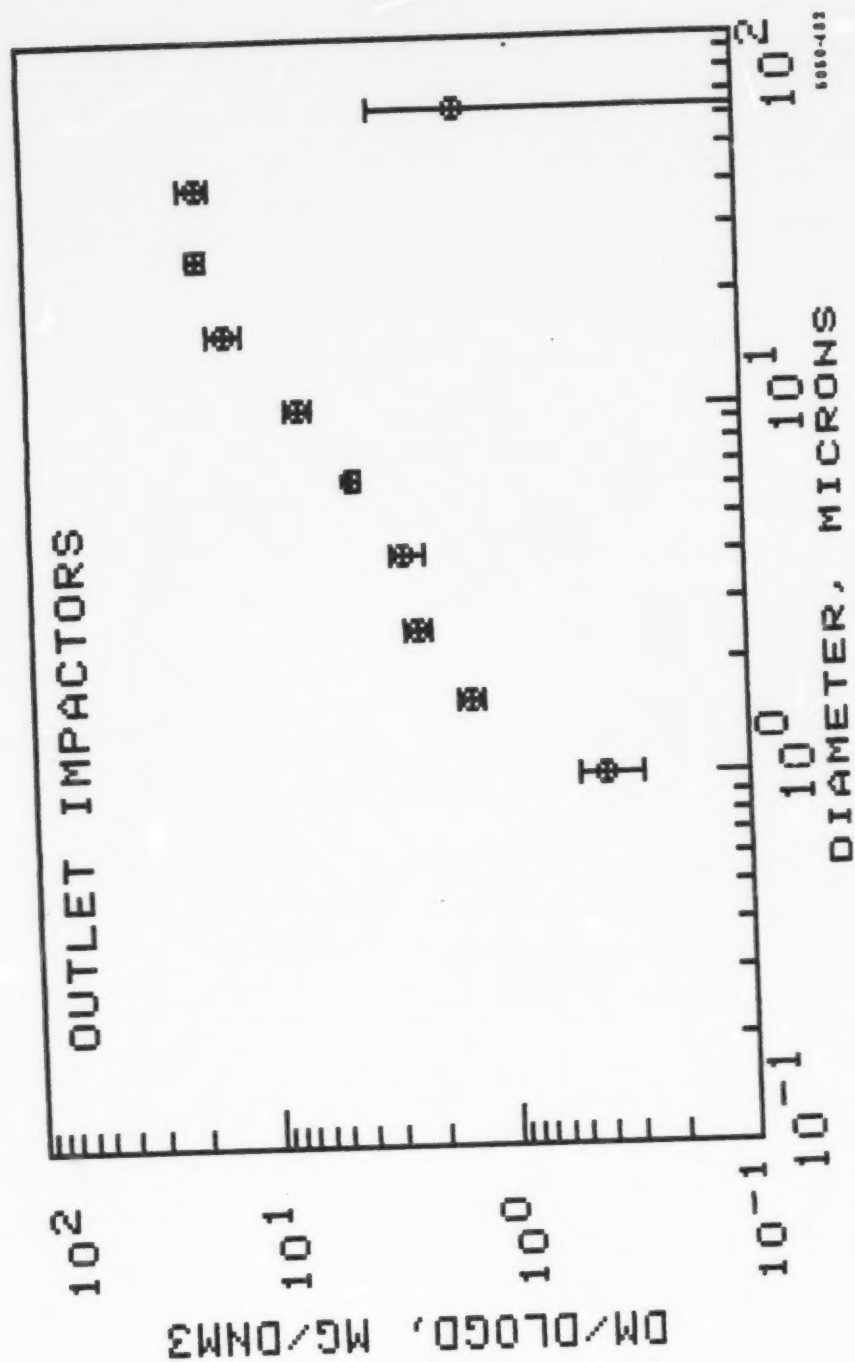


Figure 7-14. Average differential loading versus aerodynamic size for all outlet impactor runs (EGR/SIM-5 Comparison Test 2).

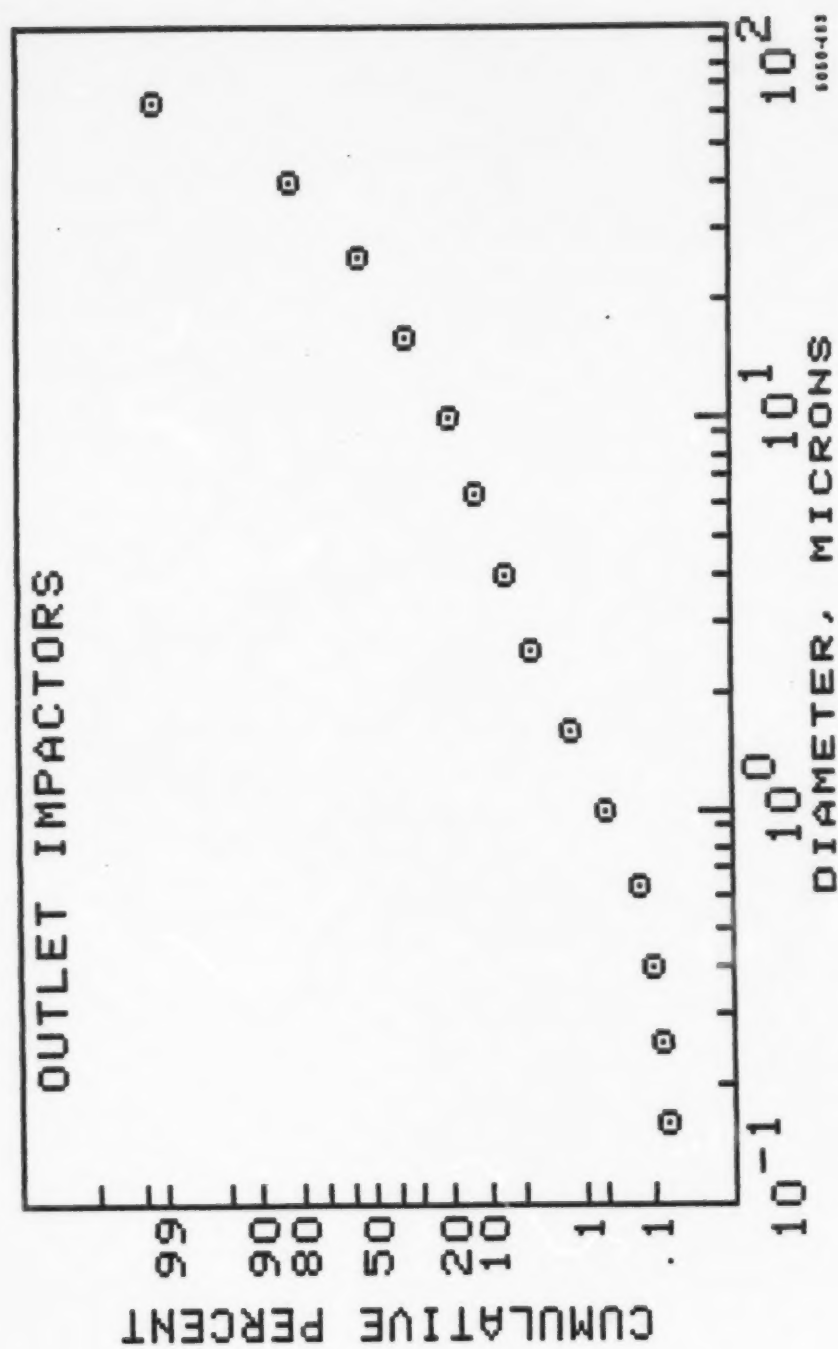


Figure 7-15. Average cumulative percent versus aerodynamic size for all outlet impactor runs (EGR/SIM-5 Comparison Test 2).

Table 7-6. Method 17 Total Particulate Test Results
at Control Device Outlet

<u>Date</u>	<u>Run</u>	<u>Concentration</u>	<u>(mg/dncm)</u>	<u>% Isokinetic</u>
10/31/84	CSO-MT(1)	12.11	11.4	92.7
10/31/84	CSO-MT(2)	14.99	14.4	95.5
11/1/84	CSO-MT(3)	14.74	13.9	92.9
11/2/84	CSO-MT(5)	22.48	21.0	92.1
11/2/84	CSO-MT(6)	15.94	14.9	92.2
11/6/84	CSO-MT(7)	18.21	17.3	93.9
11/6/84	CSO-MT(8)	10.85	10.6	96.6

Average 15.62 ± 3.58 (95% confidence, standard deviation = 3.9)

Table 7-7. Comparison of PM₁₀ Concentrations at the Inlet

	<u>No. of Observations</u>	<u>Average^a</u>	<u>95% Confidence Limits^a</u>
Impactor	5	613	±102
SIM-5	6	716	±69
EGR	6	803	±90
Difference:			
SIM-5 - EGR	6	- 87(-11%)	±74(±9%)
Impactor - SIM-5		-103(-16%)	±105(±16%)
Impactor - EGR		-190(-27%)	±116(±16%)

^aAverages and confidence limits are in mg/dncm unless otherwise shown.

Table 7-8. Comparison of Total Particulate Concentrations at the Inlet

	<u>No. of Observations</u>	<u>Average^a</u>	<u>95% Confidence Limits^a</u>
Impactor	5	4022	±444
SIM-5	6	3590	±444
EGR	6	3648	±547
Method 17	11	3077	±702
Difference:			
SIM-5 - EGR	6	-58(-1%)	±722(±21%)
Difference:			
Impactor - SIM-5		432(11%)	±533(±14%)
Impactor - EGR		374(10%)	±602(±16%)
Difference:			
Method 17 - Impactor		-945(-27%)	±758(±21%)
Method 17 - SIM-5		-513(-15%)	±766(±23%)
Method 17 - EGR		-571(-17%)	±810(±24%)

^aAverages and confidence limits are in mg/dncm unless otherwise shown.

Table 7-9. Comparison of PM₁₀ Fractions at the Inlet

	<u>No. of Observations</u>	<u>Average</u>	<u>95% Confidence Limits</u>
Impactor	5	15%	±1.7%
SIM-5	6	20%	±2.7%
EGR ^a	5	21%	±1.4%
Difference:			
SIM-5 - EGR ^a	5	-0.5%	±1.7%
Difference:			
Impactor - SIM-5 ^a	5	-5%	±2.8%
Impactor - EGR ^a	4	-6%	±1.9%

^aOutlier analysis (Grubbs and Beck, 1972) indicates that the EGR value in Test Set 3, 27.3%, should be excluded at the 95% confidence level. When this value is included the EGR result was 22.2% ±6.9%, the SIM-5 EGR difference was -2.1% ±5%, and the Impactor EGR difference was -7% ±2.9%.

Table 7-10. Comparison of Particulate Concentrations:
Impactors to Method 17 at the Outlet

	<u>No. of Observations</u>	<u>Average^a</u>	<u>95% Confidence Limits^a</u>
<u>PM₁₀</u>			
SIM-5 Impactor	10	2.9	±0.28(±10%)
<u>Total Mass</u>			
SIM-5 Impactor	10	14.5	±0.9(±6%)
Method 17	7	15.6	±3.6(±23%)
Difference:			
SIM-5 Impactor - Method 17	7	-1.1(-7%)	±3.3(±22%)
<u>PM₁₀ Fraction</u>			
SIM-5 Impactor	10	19.9%	±2.2%

^aAverages and confidence limits are in mg/dncm unless otherwise shown.

each technique are given first in each table. Then differences in techniques are given. EGR and SIM-5 measurements were analyzed as paired samples; i.e., confidence limits given for the SIM 5-EGR difference were calculated from differences between runs in individual pairs. Confidence limits given for other combinations of techniques were obtained assuming independent samples.

SIM-5 EGR Differences

The differences between SIM-5 and EGR for these tests are of primary interest. The observed difference for PM_{10} (Table 7-7) was -87 ± 74 mg/dncm or $-11 \pm 9\%$, with SIM-5 results lower than EGR. The observed difference for total particulate (Table 7-8) was -58 ± 722 or $-1 \pm 21\%$. The observed difference for PM_{10} fraction was $-0.5 \pm 1.7\%$ after outlier analysis as indicated in Table 7-9. A significant difference was observed for PM_{10} concentrations, while variation obscured differences in total particulate concentration and PM_{10} fraction.

Sources of variation in these measurements were of two types. One type was associated with the procedure such as anisokinetic sampling, recovery of sample from the cyclones, and weighing. The other was associated with the aerosol stream. Since the two probes could not be colocated, changes of the relative concentrations between two sample points during a pair of runs contributed to differences in the samples obtained by each probe. This type of variation (temporal variation of a spatial map of concentration) is suggested by the impactor data in Table 7-3; the relative concentrations between ports varied from impactor set-to-set. Estimates of the relative magnitudes of these two sources of variation are of interest but beyond the scope of this work.

The source of the difference between SIM-5 and EGR can be attributed to differences in cutpoint due to the effects of the gas recycle, statistical uncertainty beyond the 95% confidence level, or anisokinetic sampling error.

SIM-5 and EGR Compared to Impactors and Method 17

The differences between impactor and SIM-5 and EGR are also given in Tables 7-7 through 7-9. The observed difference of PM_{10} for impactors and the SIM-5 cyclone, -103 ± 105 mg/dncm or $-16 \pm 16\%$, was obscured by variation but a difference, impactor results lower than SIM-5 results, is strongly suggested. The observed difference of PM_{10} for impactors and the EGR cyclone, -190 mg/dncm or -27% , is clearly significant at 95% confidence. PM_{10} concentration measured with impactors was lower than that measured with the EGR cyclone.

The differences in total particulate concentration between impactors and SIM-5 and EGR were obscured by variation, both differences estimated to be about 10% (impactor values higher) with 95% confidence limits of about $\pm 15\%$. Differences of Method 17 from SIM-5 and EGR were also obscured by variation, both differences estimated to be about -16% (Method 17 values lower) with confidence limits of $\pm 23\%$. Total concentration measured by Method 17 was found to be significantly lower, $-27 \pm 21\%$, than the impactor results.

There appears to have been significant differences in PM_{10} fraction between impactors and both SIM-5 and EGR cyclones, estimated at -5% , impactor values lower than SIM-5 and EGR values. This difference must be assumed to indicate error in the size cut of Cyclone I or the upper stages of the impactor.

These differences (SIM-5 and EGR compared to impactor and Method 17) were also calculated for pairs of runs. For each combination of techniques, runs were paired which were most nearly simultaneous in time. This type of analysis did not yield a significantly different view of the results.

The differences between PM_{10} results from different techniques observed in this test at the inlet are not severe, but high enough to indicate that process variation was not the cause. Anisokinetic sampling error and/or uncertainties in cutpoint could be the source(s). It would be of interest to correct these data for anisokinetic sampling error but those calculations for the numerous measurements involved in this test are beyond the scope of this investigation.

SIM-5 Impactors and Method 17 at the Outlet

Table 7-10 summarizes the outlet results. The degree of variation with the SIM-5 impactor measurements was relatively small. Variation of Method 17 results was higher ($\pm 23\%$), probably because impactors were operated for longer time periods (8 hours) compared to the Method 17 runs (2 hours). The observed difference between SIM-5 impactors and Method 17 was 7%, substantially smaller than the run-to-run variation which resulted in confidence limits of $\pm 22\%$.

SECTION VIII

CONCLUSIONS FROM FIELD TESTING

COMPARISON OF MEASUREMENTS WITH DIFFERENT TECHNIQUES

As described in Sections IV-VII, the EGR and SIM-5 techniques were tested at four sampling locations at three coal fired utility boilers. The sites were selected to provide a range of particulate concentrations (15-4000 mg/dncm) and duct velocities (15-100 ft/sec), significant fractions of particulate matter larger than 10 micrometers (50-80%), and substantial velocity non-uniformity. At each site the EGR and SIM-5 measurements were compared with reference measurements of PM_{10} and/or total particulate concentrations, and at two sites the EGR and SIM-5 measurements were run simultaneously and compared to each other. Table 8-1 contains a summary of these comparisons for the field tests in this report.

Several conclusions may be drawn from the field data in summary Table 8-1 as well as the more complete data sets contained in Tables 4-3, 4-6, 5-3, 5-7, 6-2, 6-5, 7-3, 7-7, 7-8, and 7-10. First, in every case, the average concentrations measured using different techniques agreed within the combined 95% confidence intervals. Since these intervals for some tests reflect a substantial degree of variation presumably due mostly to source fluctuations, a more meaningful comparison can be drawn from paired-run analysis of the simultaneous measurements indicated in Table 8-1. Since source fluctuations cancel to first order in the comparisons, the confidence intervals are smaller and some observed differences are found to be statistically significant. Thus, for example, the EGR concentrations for both total mass and PM_{10} are significantly lower than the SIM-5 concentrations at Site 2. Likewise, the EGR concentrations are higher than the SIM-5 values at Site 3. Such differences, even when significant at the 95% confidence level, are not consistent in direction from site to site, and are typically on the order of 10%. These differences may only reflect differences in operating conditions like those discussed in Section VI for Site 2. We conclude that PM_{10} measurements using each technique can be expected to compare well with the other and with those using other reference techniques. Likewise, EGR measurements of total mass concentration may be expected to compare well with Method 17 measurements where particulate catches are sufficient to allow good recovery from the EGR sampler. Although SIM-5 was designed primarily for measurement of PM_{10} concentrations, in the present test series SIM-5 total mass measurements fell within 15% of values from the EGR and other isokinetic samplers.

PRACTICAL SAMPLING CONSIDERATIONS

The tests in this series represent the first field trials of each PM_{10} technique. Thus, it is not surprising that some modifications and improvements to each technique were made as a result of field experience. Likewise, other difficulties became apparent which could not be adequately addressed in this project. Some of these are summarized below.

Table 8-1. Percentage Differences in Particulate Concentrations
Measured During Test Series^a

	Number of Replications	PM ₁₀	Total Concentration
EGR Initial Test - Site 1			
EGR Cyclone - Isokinetic Cyclone ^b	4	-8.3±27%	9.0±29%
EGR - Method 17 ^b	8		-11.5±8.3%
SIM-5 Initial Test - Site 1			
SIM-5 - Method 17 ^b	3		-16±32%
SIM-5 - Isokinetic Impactors ^b	4	-1.8±22%	8.0±65%
EGR/SIM-5 Comparison Test - Site 2			
EGR Cyclone - SIM-5 Cyclone ^b	5	-15.5±6.5%	-9.2±8.5%
EGR - Isokinetic Impactors	5-6 ^c	-11±31%	1.3±38%
SIM-5 - Isokinetic Impactors	7-6 ^c	3.8±25%	14±31%
EGR/SIM-5 Comparison Test - Site 3			
Inlet			
EGR - SIM-5 ^b	6	11±9.8%	1.7±21%
EGR - Impactor	6-5 ^c	27±16%	-9.8±16%
SIM-5 - Impactor	6-5 ^c	16±16%	-11±14%
Outlet			
SIM-5 Impactor - Method 17	6-7 ^c		-7.4±23%

a All differences and confidence intervals expressed as percentages of the mean value. Confidence intervals represent 95% significant level.

b These comparisons were analyzed as pairs since the measurements were simultaneous.

c Where two numbers of replications are given, the first number corresponds to the first listed device and the second to the second device.

Equipment Changes to EGR Train

Several hardware components of the EGR train were upgraded during the course of the four field tests.

- The prototype EGR control module had a thin wall, flexible stainless steel tubing between the recycle control valve (V_3 in Figure 3-2) and the recycle gas exit. This tubing developed a leak in Test 1 and was replaced.
- Arrangement of the EGR recycle lines, nozzle, and pitot lines on the instack end of the probe was a frequent source of difficulty in EGR Tests 1 and 2. The primary source of the problem was the difficulty of aligning these extra lines to allow easy fit through typical four inch sampling ports. Before the final test the instack lines were replaced with flexible tubing. This change helped the mounting and alignment problems, while allowing flexibility in the choice of samplers. When a sampling train with specified instack hardware is constructed for routine use, a more rigid permanent mounting arrangement should be designed.
- It was discovered on the first EGR/SIM-5 combined test that the EGR sample and recycle lines could be reversed. After this test, an umbilical line with different quick disconnect connectors was constructed to eliminate this possibility.

Development of SIM-5 Protocol

At the beginning of the project, the recommended SIM-5 protocol (Farthing, 1983) was defined by the step-by-step procedure contained in Table 3-1. In order to simplify the procedure so that a technician member of a sampling team could make the on-the-spot sampling decisions necessary for SIM-5, a setup calculation sheet (Table 7-1) was developed before the final test of this series. The table requires only a pocket calculator with typical scientific functions. In the course of the field series, SIM-5 calculations were also performed using modifications of BASIC programs for Apple II series microcomputers.

Also during the course of the project, further estimates were made of the error to be expected in SIM-5 testing. Rough limits were calculated for several measured and hypothesized aerosol size distributions. The error which may be incurred with SIM-5 depends upon the shape of the size distribution below aerodynamic particle diameter of 10 μm . As the fraction of particles near 10 μm increases the potential for error increases. This subject is addressed in more detail by Farthing, et al. (1985). The maximum error possible with SIM-5 sampling an aerosol of 10 μm particles is 20%. However, for real aerosols emitted by sources the maximum error incurred will be much less than this. The maximum level for each type of source could be determined by calculations similar to those described by Farthing et al. (1985), from existing source data.

Inertial Samplers

The PM_{10} measurements during this test were made with two inertial sizing devices. All EGR measurements were made using SoRI Cyclone I as a PM_{10} sampler, as were the comparison SIM-5 measurements taken simultaneously with EGR measurements in the last two tests. All other SIM-5 measurements were made using cascade impactors (UW Mark V with Flow Sensor right angle impactor precollectors), as were various reference samples during the course of the testing program. Both devices have strengths and weaknesses for PM_{10} sampling, and PM_{10} samplers of both types are feasible.

As compared with cyclones, cascade impactors can be used for lower particulate concentrations, recovery of the collected particulate matter is easier, greater size resolution is possible since more sizing stages are available, and performance is predictable over a wider range of operating conditions. In view of these advantages and the fact that many more impactors than cyclones have been sold, we anticipate that impactors will be a more popular choice for PM_{10} sampling. However, impactors are subject to particle bounce, overloading, and substrate interactions, so single stage PM_{10} operation is not acceptable at this time with an impactor PM_{10} sampler. In contrast, cyclones have inherently higher mass loading capacity, they are more tolerant of higher than anticipated concentrations, and they are not subject to particle bounce or substrate interactions. Thus, a one or two stage PM_{10} cyclone sampler is generally feasible. Difficulties of cyclones include the fact that recovery of collected particulate matter is more difficult than from impactors, especially for extremely light particulate catches. In any case, more sample is required than for impactors. In addition, the performance of a given cyclone is not as predictable a priori as a given impactor stage. In order to determine the cyclone flowrate which produces a given cut diameter (such as $10\mu m$), calibration measurements extending over the range of expected gas conditions must be performed and empirical predictive equations fit to these data. These equations do not scale in a predictable way with gas temperature and flowrate, so they cannot, with confidence, be extrapolated far beyond the range of the experimental calibration points. Thus development of a useful cyclone for source sampling involves much more calibration effort than an impaction stage, and the performance of the cyclone cannot be predicted with as much certainty at duct gas temperature, pressure, or composition outside its normal operating range.

The best summary analysis of these factors is that both types of PM_{10} samplers may be used for a range of applications. A cyclone train is to be preferred where a single stage PM_{10} sampler is required or where very high or variable particulate concentrations are to be sampled. A cascade impactor sampler is to be preferred where detailed size information as well as PM_{10} concentration is required, where the particulate concentrations are relatively low (below about $20mg/dncm$), or where conditions outside the calibration range of available cyclones exist (that is, temperatures of over $250^{\circ}C$, pressures significantly different from normal atmospheric, or gas compositions significantly different than air or typical combustion offgases).

In view of these general comments, some obvious needs for further research can be listed. Given the desirability of an impactor PM_{10} train,

development of an EGR impactor train is in order. Such a train might consist of a commercial impactor preceded by a right-angle geometry impactor precollector with a recycle nozzle.

Further development work is also desirable with the current PM_{10} Cyclone SoRI-I. The current design of Cyclone I has been calibrated in air with D_{50} at or near $10\mu m$ for temperatures of 23, 150, and 204 C. A few other flowrate/ D_{50} combinations have been investigated at ambient and elevated temperatures, as shown in Figure 3-9. Further calibration work at several temperatures is recommended before Cyclone I is used as a reference PM_{10} sampler.

Alternate geometries for Cyclone I should also be considered. This cyclone is a modified, bottom-exit cyclone in which the gas exit tube passes through the collection cup and cyclone body rather than the top. This design allows the sampling nozzle to be positioned 1 inch from the far duct wall as compared with about 3.5 inches for a conventional top exit geometry. The significance of this can be seen when considering EPA Method 1 requirements. For a minimal 12 point traverse in a circular duct (6 points per diameter), the first traverse point will be less than 3.5 inches from the far duct wall for duct diameters up to 80 inches. The current cyclone design allows the first traverse point to be reached in ducts over 23 inches. The modified, bottom-exit geometry thus allows significantly greater flexibility in reaching all traverse points in medium-diameter ducts.

Nevertheless, there are still excellent reasons to specify a conventional top-exit geometry for a PM_{10} cyclone. The outlet tube of a bottom-exit cyclone collects significant amounts of particulate matter with diameters up to about 75% of the cyclone D_{50} . This particulate is typically recovered with the next cyclone in the train, and poses no great problem since cyclone train catches are commonly on the order of hundreds of milligrams. However, one contemplated PM_{10} configuration is a single cyclone plus filter train. Such a train would give a good measure of PM_{10} only if the particulate deposit inside the exit tube can be recovered efficiently; this may be a problem if a single cyclone train is used for very light loadings. A more significant problem with the bottom exit configuration is the deposition of particulate matter on the outside of the exit tube. These particles are counted with the cyclone catch, and again pose no problem if they remain in the cyclone interior. However, these deposits are subject to reentrainment or transfer into the exit tube if the cyclone catch is large or if the cyclone is jarred significantly during operation or prior to recovery. Such misdirected particles would result in an overestimate of this PM_{10} fraction of the total particulate matter present. Both these potential problems would be minimized in a conventional top-exit cyclone.

Existing data characterizing right-angle impactor precollectors is also inadequate for sampling at various types of conditions. The devices appear to be acceptable substitutes for bent nozzles, and useful means of preventing first stage overloading. However, only limited calibrations have been performed for sizes near $10\mu m$ at a few gas flowrates and nozzle sizes. Based on these data the D_{50} of the precollector can be predicted with some confidence over a limited range of operating conditions. However, since the precollector nozzle is closely coupled with the impaction jet, the D_{50} may not scale

according to theory for some sampling conditions. In particular, at high duct velocities the precollector D_{50} may well be smaller than calculated from current data. We recommend future study include more thorough calibration of the right angle impactor precollector if it is to be used in PM_{10} sampling.

Pitot Heads

Recurrent unexpected problems were observed with the S-type pitot tubes used for velocity measurements in this test program. When the pitot heads were mounted on the sampling probes beside the inertial sizing device, they were found to have significantly different calibrations than the same pitot heads mounted alone or with Method 17 nozzles. In some cases, the pitot calibration observed in the field was significantly different than that found in the 12 inch diameter wind tunnel. Although the precise reason for this observed effect was not determined, the differences in the velocities at Sites 2 and 3 measured with different pitot tubes are indications of this effect. Finally, alignment of the pitot head and sampling nozzle proved more difficult to establish and maintain than with Method 5.

The probable cause for all these problems is the proximity of the relatively massive PM_{10} inertial sampling device to the pitot head. Possibly the sampler perturbed the gas flow in the vicinity of the pitot head. In small ducts where the sampler would obstruct a significant fraction of the duct area, the anticipated effect on the pitot would be greater. Criteria for pitot positioning relative to PM_{10} sampling nozzles need to be established. Since inertial sizing devices are typically run without colocated pitot heads, such criteria are not well established and we were unable to find any quantitative guidance in the literature on the subject. We recommend that conditions for use of S-type pitot tubes with instack sizing devices be a specific item for future study.

SECTION IX

PROJECT QUALITY ASSURANCE

Development and validation of emission test methods require test data of documented reliability. Since the measurements performed in a methods evaluation project are typically not routine, it is imperative that an adequate quality assurance program specific to the project be developed and implemented. The Quality Assurance guidelines for this task are outlined in the Quality Assurance Project Plan (QAPP) submitted to and approved by EMSL. QA activities described in the QAPP may be summarized in the following categories: equipment calibration and maintenance; blanks and controls; data recording; custody and validation; QC checks and audits; and corrective action. These activities will be described in detail in the following sections.

EQUIPMENT CALIBRATION AND MAINTENANCE

All dry gas meters and flow orifices used in the EGR-SIM-5 field tests underwent a thorough initial calibration with calibration checks after each test. Rental equipment was handled in the same manner.

The initial calibration of each gas meter was performed at five flowrates ranging from approximately 0.1 to 1.3 acfm. At the two lowest flowrates, a wet test meter with a capacity of 0.4 acfm (estimated accurate to 0.5 percent) and a 1.5 cfm laminar flow element were used as standards. At the higher flowrates, only the LFE was used. The calibration constant for each dry gas meter was calculated as the average of the calibration constants from the two wet test meter runs because the flowrates used in this program were in this range. The calibration runs using the LFE were performed to insure consistency of dry gas meter performance over the flow range within the precision of the LFE measurements.

The post test calibration checks of the dry gas meters and orifices were performed simultaneously. Each post test check consisted of two ten-minute runs at the same flowrate. The flowrate was set to be approximately the same as a flowrate used in the initial calibration of the dry gas meter and consistent with flows encountered in the field.

Table 9-1 shows the initial calibration constants and all post test checks for each of the dry gas meters used. The initial calibration constant was considered to be valid if the post test check yielded a result within two percent of the original value.

Two of the three dry gas meters (RAC STAKSAMPLER #S1222, EGR, and Nutech SRI #6180) used on the EGR shakedown (Test 1) did not meet this criterion and all three were recalibrated. In the case of RAC STAKSAMPLER #S1222 and the EGR dry gas meter, the new calibration constant was used for the reduction of all Test 1 subsequent field data. Recalibration of Nutech SRI #6180 suggested the dry gas meter had sustained damage during transport and the meter was replaced prior to Test 2. All data collected using this sampling train was reduced using sample volumes obtained from the orifice calibration and the sample run time.

Table 9-1. Dry Gas Meter Calibration Data

Dry Gas Meters (γ)	Calibration Constants					
	Initial	Post Test #1	Post Test #2	Pre Test #3	Post Test #3	Post Test #4
RAC STAKSAMPLER #S1222	1.0178	1.0051	1.0128	0.9944	1.0013	0.9770
EGR #	0.9650	1.0183	1.0171	1.0119	1.0138	0.9979
Rockwell #6830278	0.9847	NA	0.9885	-- ^b	0.9848	0.9928
Singer #F277177	0.9977	NA	1.0033	-- ^b	0.9871	0.9931
Singer #F277178	0.9880	NA	0.9780	0.9887	0.9971	0.9882
Nutech Rental #2014124	0.9926	NA	NA	NA	NA	0.9828
Nutech Rental #2014125	1.0097	NA	NA	NA	NA	1.0100
Nutech SRI #6180	1.0022	1.117 ^a	NA	NA	NA	NA

^aThis gas meter replaced prior to Test #2.

^bPost test #2 used as pretest #3 calibration check.

The post test calibration check performed on RAC STAKSAMPLER #S1222, used to run the SIM-5 cyclone during Test 4, was 2.4% different from the pretest value. A recalibration of the meter was not performed, however, for two reasons. First, an inspection of the calibration constants for this meter and the EGR dry gas meter indicated the variation between the post test calibration check and the initial calibration were comparable in both magnitude and sign. As the major relevance of the SIM-5 data is in comparison to the EGR data, it was felt that any error introduced by using the initial calibration constant would be negligible. Furthermore, the dry gas meter calibration did pass Method 5 criterion.

In most cases, a pretest calibration check was not considered necessary if the meter was not used since the post test check for the previous test. A pretest calibration check was performed, however, on RAC STAKSAMPLER #S1222, SINGER #F277178, and the EGR dry gas meter prior to Test 3. This pretest calibration check was performed on RAC STAKSAMPLER #S1222 and the EGR dry gas meter because of changes in the plumbing of these systems. The Singer #F277178 dry gas meter was used on a field test not associated with the EGR-SIM-5 project prior to Test 3 and, therefore, required another calibration check.

Table 9-2 shows the calibration constants, a and b , obtained from initial calibration and all post test checks of all flow metering orifices. Table entries represent percent difference between the calibration curve flowrate and the actual flowrate through the orifice. The QAPP targeted $\pm 5\%$ as the point at which recalibration of the orifice would be performed.

Table 9-3 shows the calibration constant, C_p , for all pitots used on EGR-SIM-5 field tests. As the table indicates, each pitot was calibrated with the appropriate hardware mounted on the probe as experience indicated this had a significant effect on the C_p value. Whenever possible, pitot calibrations were performed in the wind tunnel prior to the field test.

As described in Section IV, some on-site calibration of pitots was required for Test 2 configurations requiring two or three colocated University of Washington impactors. These calibrations were performed in the duct using a wind tunnel calibrated S-type pitot as the reference. The pressure differential was too low (0.003 inches H_2O) to allow use of a standard pitot. The procedure involved positioning the calibrated S-type pitot at the appropriate point and noting the pressure differential. The sampling probe or probes, mounted with a S-type pitot and the appropriate sampling hardware was then inserted into the duct next to the calibrated pitot. The pressure differential registered by the calibrated pitot was checked to insure no change was caused by the introduction of the sampling probe before recording the pressure differential of both pitots. The pitot coefficient was then calculated for the non-calibrated pitot.

The same procedure was used to recalibrate the EGR pitot used on EGR/SIM-5 Test 2. The new pitot coefficient was used for all data reduction.

Table 9-2. Orifice Calibrations, $Q = a \left(\frac{\Delta H T}{P} \right)^b$, acfm

Orifice Constants	Initial	Post Test #1	Post Test #2	Post Test #3	Post Test #4
180 A a = b =	0.721 0.499	0.693 ^a 0.480			
B	0.726 0.502	0.701 ^a 0.523			
E	0.695 0.501	1.0%			
F	0.737 0.527				-5.0%
K	0.652 0.483				-0.3%
C	0.395 0.543				-4.4%
D	0.366 0.507				-0.8%
093 A	0.214 0.516		-4.6%	0.5%	-4.0%
B	0.214 0.522			3.5%	2.7%
C	0.222 0.533			2.4%	
D	0.217 0.520		0.2%	-1.4%	
E	0.155 0.504				0.40%

^aThese orifices recalibrated due to previous calibration problems.

Note: Entries represent percent difference between calibrated flowrate, Q , and actual flowrate in acfm.

Table 9-3. Pitot Calibrations

I.D.	Configuration	Side A	Side B
<u>Test #1</u>			
EGR	Dual cyclone colocated with mass train filter	0.849	0.824
<u>Test #2</u>			
#19	"S" type pitot mounted on probe	0.774	0.780
#18	U.W. Mark V colocated w/ 63mm mass train filter	0.800	--
#18	Two colocated U.W. Mark V impactors	0.730	--
#17	47mm mass train filter	0.830	--
#17	Three colocated U.W. impactors	0.830	--
#17	Two colocated U.W. Mark V impactors	0.740	--
#16	Two colocated U.W. Mark V impactors	0.730	--
#9	"S" type velocity probe	0.830	--
<u>Test #3</u>			
#19	U.W. Mark V impactor	0.767	--
#18	U.W. Mark V impactor	0.757	--
#18	Non-recycle Five-stage cyclone	0.757	--
#17	U.W. Mark V impactor	0.759	--
#15	Five-stage cyclone with recycle	0.747	--
Velocity	"S" type velocity pitot	0.807	0.824
<u>Test #4</u>			
#17	U.W. Mark V w/ right angle precutter	0.820	--
#16	U.W. Mark V w/ right angle precutter	0.799	--
#15	U.W. Mark V w/ right angle precutter	0.811	--
#14	U.W. Mark V w/ right angle precutter	0.840	--
R	U.W. Mark V w/ right angle precutter	0.818	--
A	U.W. Mark V w/ right angle precutter	0.851	--
N	U.W. Mark V w/ right angle precutter	0.812	--
D	U.W. Mark V w/ right angle precutter	0.844	--
Y	U.W. Mark V w/ right angle precutter	0.814	--
EGR	Five-stage cyclone with recycle	0.792	--
SIM-5	Non-recycle five-stage cyclone	--	0.732
MT-Inlet	Mass train thimble	0.769	--
MT-Outlet	47mm mass train filter	0.762	--
Velocity	"S" type velocity pitot	0.857	0.856

Prior to each field test, all nozzles likely to be used were checked for nicks and dents with any necessary repairs made before measurement of diameter. During the course of the test, nozzles were visually inspected in the lab for damage. If necessary, repairs were made and the nozzle was remeasured. Table 9-4 shows the results of these calibrations. Each entry is the average of six diameter measurements.

During the first SIM-5 test, CO₂ and O₂ concentrations in the sample gas were to be determined with Fyrite cylinders. Although the Fyrites performed well in the pretest checks at Southern Research, onsite pre-operational checks performed as described in the Fyrite instruction manual indicated that the fluid was too weak to provide accurate results. Plant monitors were, therefore, used to determine CO₂ and O₂ concentrations. Prior to EGR/SIM-5 Test 2, both CO₂ and O₂ Fyrite cylinders were recharged with new fluid according to the manufacturer's instructions. Both cylinders were then zeroed and the calibration checked with room air and a standard gas sample of known O₂ and CO₂ concentrations.

The recycle and total flow laminar flow elements (LFE's) in the EGR system were calibrated prior to the EGR shakedown (Test 1). Table 9-5 shows the initial calibration of both LFE's and all post test calibration checks. Table entries for calibration checks represent percent difference between the actual flowrate through the LFE and the flowrate obtained from the calibration curve.

The dual entries in Table 9-5 for the total flow LFE represent the calibration checks at the extreme conditions of zero and 100 percent recycle. While the percent recycle does not affect the pressure drop across the LFE, it does affect the LFE to ambient pressure differential. This results in the greater percent difference between the actual and calibration curve flowrates calculated at the higher recycle rate. To better reflect the effect of variable back pressures on the total flow LFE calibration, a twenty point calibration was performed prior to Test 4 which varied the percent recycle from zero to 100% for a constant flowrate.

QC Checks and Audits

To insure the reliability of test data, several internal quality assurance checks were performed. Prior to each field test, all equipment to be used was inspected and operated in the lab. During the field tests, pre-run leak checks were performed on the assembled sampling trains, including control boxes, probes, pitots and the sampling device. As a final check of proper system operation, partial data reduction was performed in the field to check for acceptable isokinetics.

Table 9-4. Nozzle Diameters, inches

Nozzle I.D.	Test #1 5/31/84	Test #2 7/10/84	9/10/84	Test #3 9/12/84	9/13/84	9/14/84	10/10/84	Test #4 10/16/84	10/17/84	11/2/84
EGR - A	0.259									
- B	0.186									
- C	0.123		0.1312					0.1276		
- D	0.090									
Hill Precutiter										
1-4		0.2485			0.1840		0.1858			
1-5							0.1227			
1-6										
2-4		0.2490					0.1853			
2-5			0.1875				0.1233			
2-6			0.1263		0.1230		0.1243			
3-6										
X-4		0.2485								
X-5			0.1875		0.1870	0.1850	0.1857			
X-6			0.1253		0.1230	0.1200	0.1194			
Z-4		0.2488								
Z-5										
Z-6			0.1242	0.1270	0.1220	0.1240	0.1828			
MT										
1/4-A		0.2520								
1/4-B		0.2422								
5/16-A		0.3112							0.3110	0.3115
5/16-B		0.3117							0.2533	
I-4									0.2429	
I-5									0.3120	0.3117
II-5										
III-4										
BCURA										
1-3								0.1851		
2-3								0.1857		
Non-recycle										
Cyclone										
NRG-8			0.2100							
NRG-10			0.1790							
II-9								0.1942		

Table 9-5. EGR Control Box Laminar Flow Element Calibration

	Initial	Post Test 1	Post Test 2	Pre Test 3	Post Test 3	Post Test 4
Recycle	a = 0.0086 b = 0.9033			0.00519 1.0052	0.0061 0.9753	-6.8%
Total	a = 0.01308 b = 0.9737				0.01475 0.9552	
0% Recycle				1.37%		2.75%
100% Recycle				2.12%		3.46%

In addition to the above activities, on site system audits were performed during Tests 3 and 4 by comparing dry gas meter and orifice flowrates. Although in three of the 13 audits apparent failures were observed, closer examination, as part of field corrective action, affirmed that the systems were in fact operating properly as explained below. For Test 3, audits were performed on three systems with one apparent failure. Ten audits were performed during Test 4 with two apparent failures. Apparent failure was registered when the orifice flowrate failed to fall within three percent of the dry gas meter flowrate. In the case of Test 3, a check of the orifice calibration showed that the audit flowrate was within 0.10% of the calibration flowrate for the same orifice pressure drop. On the basis of this observation, the system was passed and used during the test. Subsequent examination of the orifice calibration curve showed that the square root fit of the calibration data differed from the actual data point at the audit flowrate by approximately 7%. This suggested that while overall the calibration curve fit the data points within $\pm 3\%$, individual data points did not. Therefore, the audit procedure should have included either multiple audit data points or pass/fail criterion greater than ± 3 percent. For Test 4, the audit procedure was performed as in Test 3. Comparisons of the audit flowrate with the calibration flowrate were made in cases where the orifices apparently failed to pass the audit initially. As in Test 3, the calibration data indicated the orifices were functioning properly and the systems were passed. We intend to revise our gas meter audit procedure, and are in the process of introducing an audit procedure using a critical orifice.

Each impactor set run during the EGR/SIM-5 field tests included a blank substrate. The blank provided a correction for artificial weight gains due to reaction with stack gases and acted as a control weight for the balance. After Test 3, weight changes caused by changes in the balance were found to be greater than expected. To correct this, a control set was added to the weighing procedure. Blanks were still run to correct for the effect of stack gases on substrate weights.

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